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Assessment of Scotian Shelf Snow Crab in 2009

Évaluation intégrée du stock de crabes des neiges résidant sur le plateau néo-écossais en 2009

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ABSTRACT

Landings in 2009 were 579 and 10,648 t for northern and southern areas of Eastern Nova Scotia (ENS), respectively and 229 t for Crab Fishing Area (CFA) 4X in 2008/2009. The associated TACs were 576, 10,800 and of 230 t, respectively. Average, non-standardized catch rates were 75.7, 89.6 and 28.4 kg trap^{-1}, respectively. These catch rates represent a 125% increase for N-ENS (above the 13 year mean of 55.4 kg trap$^{-1)}$, a marginal decrease in S-ENS, and a 57% increase in CFA 4X, relative to 2008.

The capture of soft-shelled crab in N-ENS declined from 49% in 2008 to 6% in 2009, largely due to 86% of the total N-ENS landings being captured in the spring, when soft-shell catchability is lower. In contrast, in S-ENS, the capture of soft-shelled crab increased from 13% in 2008 to 19% in 2009. CFA 4X had virtually no soft-shell incidence due to their winter season. Soft-shell incidence and associated potential handling mortality will continue to be an issue in 2010 due to continued recruitment in S-ENS. By-catch of non-target species is low, being estimated to be less than 0.013% and 0.783% of total snow crab landings in ENS and CFA 4X, respectively, over the past four years.

Recruitment into the fishery is expected to continue for the next 4-5 years in all areas. High densities of adolescents between 70 to 80 mm CW (carapace width) have been observed in ENS. In CFA 4X, high densities of crab between 20 to 40 mm CW were observed. The leading edge of the current recruitment pulse began entering the fishable biomass in 2007 in S-ENS; 2008 in N-ENS; and 2009 in CFA 4X. Full entry is expected in 2011 to 2014, depending upon area. The reproductive potential of the Scotian Shelf population peaked in 2007/2008 and is now on a declining trend. Larval production should continue for another 2-3 years.

The post-fishery fishable biomass of snow crab was estimated to be 1,342 t (with a 95% confidence range of: 946 t to 2,059 t), relative to 4,836 t in 2008 in N-ENS. In S-ENS, the post-fishery fishable biomass increased to 66.2×10^3 t (with a 95% confidence range of: 55.7 to 77.2×10^3 t), relative to 45.8×10^3 t in 2008. In CFA 4X, the pre-fishery fishable biomass was 1,730 t (with a 95% confidence range of 580 to 5,070 t), relative to 1,180 t in 2008/2009. Large uncertainties are associated with the abundance estimates in S-ENS and CFA 4X due to the extreme temperature conditions and associated large-scaled shifts in spatial distributions observed in 2009.

These positive population characteristics are tempered by a number of additional uncertainties: The influence of predation, especially upon immature and soft shelled snow crab by groundfish. Large and rapid temperature swings as they can have both direct and indirect influences upon snow crab. For example, a strong warming event can have direct deleterious effects as snow crab are cold-water stenotherms. Even the very significant cooling trend observed throughout the Scotian Shelf in 2009 with an associated habitat expansion was observed can have negative indirect consequences such as the introduction or proliferation of invasive species or disease (e.g, *Hematodinium sp.*) or the reduction of gross primary production. In addition to these factors, the signs of an initial return of ecological, social and economic indicators of

system state in the direction of a low invertebrate dominated system adds, further uncertainty to the medium to long-term sustainability of the Scotian Shelf snow crab population.

Relative exploitation rates (by biomass) in N-ENS were 29% in 2009 (5% in 2008). Projections suggest that an exploitation rate between 10 and 20% may be suitable for long-term sustainability in N-ENS. Good recruitment and a significantly reduced soft-shell handling result in a positive outlook. However, the rapid and unexpected decline in fishable biomass in 2009 tempers this positive outlook. Until a strong and persistent increase in fishable biomass is observed, a decrease in TAC is recommended.

Relative exploitation rates in S-ENS were 14% in 2009 (15% in 2008). Maintaining exploitation rates between 10% and 30% may provide the greatest longevity to this fishery. Good recruitment suggests a positive outlook; however, the capture of soft shell crab remains an important issue for this fleet. An increase in TAC is recommended.

Relative exploitation rates in CFA 4X for 2009/2010 were 12%; for 2008/2009, they were 16%. Exploitation rates between 10% and 30% may provide the greatest longevity to this fishery. A moderate increase in TAC is recommended.

RÉSUMÉ

En 2009, les débarquements en provenance des secteurs nord et sud de l'est du plateau néo écossais (N-EPN. É. et S-EPN. É.) se sont chiffrés à 579 et 10 648 t, respectivement, alors que les débarquements de la zone de pêche du crabe (ZPC) 4X pour 2008 2009 étaient de 229 t. Les TAC connexes se chiffraient à 576 t, 10 800 t et 230 t, respectivement. Les taux de captures moyens non normalisés étaient respectivement de 576, 10,800 et 230 t, et de 75,7, 89,6 et 28,4 kg/casier-1. Ces taux de captures représentent une hausse de 125 % pour le N-EPN. É. (par rapport à la moyenne sur 13 ans, qui est de 55,4 kg/casier-1), une baisse marginale pour le S EPN. É. et une hausse de 57 % pour la ZPC 4X, par rapport à 2008.

Les captures de crabes à carapace molle dans le N-EPN. É. sont tombées de 49 % en 2008 à 6 % en 2009, en grande partie parce que 86 % de tous les débarquements venant de ces eaux ont été capturés au printemps, quand la capturabilité des crabes à carapace molle est moindre. Par contre, dans le S EPN. É., les captures de crabes à carapace molle ont augmenté, passant de 13 % en 2008 à 19 % en 2009. Il n'y a pratiquement pas eu de captures de crabes à carapace molle dans la ZPC 4X, la pêche s'y déroulant en hiver. La question de la présence des crabes à carapace molle et de leur mortalité possible par manipulation restera problématique en 2010, en raison de la poursuite du recrutement dans le S EPN. É. Les captures accessoires d'espèces non ciblées sont faibles; on les estime à moins de 0,013 % et 0,783 % des débarquements totaux de crabe des neiges des quatre dernières années dans tout l'est du plateau néo-écossais (EPN. É.) et dans la ZPC 4X, respectivement.

Le recrutement à la pêche devrait se poursuivre au cours des 4 à 5 prochaines années dans toutes les eaux. On a observé de fortes densités d'adolescents de 70 à 80 mm de LC (largeur de carapace) dans l'EPN. É. et de fortes densités de crabes de 20 à 40 mm de LC dans la ZPC 4X. Les premiers crabes de la vague de recrues ont commencé à intégrer la biomasse exploitante en 2007 dans le S EPN. É., en 2008 dans le N EPN. É. et en 2009 dans la ZPC 4X. Le plein recrutement devrait se produire de 2011 à 2014, selon la zone. Le potentiel de reproduction de la population du plateau néo écossais a culminé en 2007 2008 et il suit maintenant une tendance à la baisse. La production de larves devrait se poursuivre pendant encore 2 à 3 ans.

Dans le N EPN. É., la biomasse exploitable de crabe des neiges après la pêche a été estimée à 1 342 t (intervalle de confiance de 95 % : 946 t-2 059 t), alors qu'elle était de 4 836 t en 2008). Dans le S EPN. É., la biomasse exploitable de crabe des neiges après la pêche a été estimée à 66,2 × 103 t (intervalle de confiance de 95 % : 55,7 77,2 × 103 t), alors qu'elle était de 45,8 × 103 t en 2008. Dans la ZPC 4X, la biomasse exploitable de crabe des neiges avant la pêche était de 1 730 t (intervalle de confiance de 95 % : 580 5 070 t), comparativement à 1 180 t en 2008 2009.Les estimations de l'abondance dans le S EPN. É et dans la ZPC 4Z sont très incertaines, en raison des conditions de température extrêmes et des vastes changements connexes dans les répartitions spatiales en 2009.

D'autres incertitudes viennent contrecarrer ces tendances positives de la population. L'influence de la prédation par le poisson de fond, en particulier sur les crabes des neiges immatures ou à carapace molle, et les changements vastes et rapides de la température peuvent influer directement et indirectement sur le crabe des neiges. Par exemple, un fort réchauffement peut avoir des effets délétères directs sur le crabe des neiges, qui est un crustacé sténotherme d'eau froide. Même la très nette tendance au refroidissement observée sur l'ensemble du plateau néo écossais en 2009, associée à une expansion de l'habitat, peut avoir des conséquences négatives indirectes comme l'introduction ou la prolifération de maladies ou d'espèces

envahissantes (p.ex. Hematodinium) ou la réduction de la production primaire brute. En plus de ces facteurs, les signes d'un retour initial des indicateurs écologiques, sociaux et économiques de l'état de l'écosystème vers un écosystème à faible dominance des invertébrés ajoutent encore de l'incertitude quant à la viabilité à moyen et long termes de la population de crabe des neiges du plateau néo écossais.

Le taux d'exploitation relatif (par rapport à la biomasse) dans le N EPN. É. était de 29 % en 2009 (5 % en 2008). Selon les projections, un taux d'exploitation de 10 à 20 % peut être viable à long terme dans le N EPN. É. En raison du bon recrutement et d'une baisse importante de la manipulation de crabes à carapace molle, les perspectives sont favorables. Toutefois, le déclin rapide et inattendu de la biomasse exploitable en 2009 est une ombre au tableau. On recommande de diminuer le TAC jusqu'à ce qu'on observe une hausse nette et persistante de la biomasse exploitable.

Le taux d'exploitation relatif dans le S EPN. É. était de 14 % en 2009 (15 % en 2008). Le maintien entre 10 % et 30 % du taux d'exploitation pourrait contribuer à la longévité de cette pêche. Un bon recrutement permet de penser que les perspectives sont favorables; toutefois la capture de crabes à carapace molle reste un important problème pour la flottille qui pêche dans ces eaux. Une hausse du TAC est recommandée.

Le taux d'exploitation relatif dans la ZPC 4X en 2009 2010 était de 12 %; en 2008 2009, il avait été de 16 %. Un taux d'exploitation se situant entre 10 % et 30 % pourrait contribuer à la longévité de cette pêche. Une hausse modérée du TAC est recommandée.

MANAGEMENT

The SSE snow crab fishery is managed as three main areas: Northern-Eastern Nova Scotia (N-ENS), Southern-Eastern Nova Scotia (S-ENS) and Crab Fishing Area (CFA) 4X (Figure 1, Table 1). These areas are *ad hoc* divisions based upon political, social, economic and historical convenience, with little biological basis.

Fishing seasons have also had a complex evolution based upon economic, safety and conservation considerations: severe weather conditions; catch of soft-shell and white crab; disruption of mating periods; and overlap with other fisheries, especially lobster. Fom 1982 to 1993, the management of the ENS fisheries was based on effort controls (size, sex, shell-hardness, season, license, trap limits). Additional management measures were introduced from 1994 to 1999: Individual Boat Quotas (IBQs), Total Allowable Catches (TACs), 100% dockside monitoring, mandatory logbooks and at-sea monitoring by certified observers (currently, 5%, 10%, and 10% in N-ENS, S-ENS, and CFA 4X, respectively). Vessel Monitoring Systems (VMS) have been implemented in S-ENS and voluntary management measures requested by fishers were also introduced in some areas, such as a shortened fishing season and reduced numbers of traps. The designation of a "temporary licence" holder was dropped in 2005.

In 2006, the soft shell protocol was modified in S-ENS due to the expectation of an increased incidence of soft-shelled snow crab and the potential harm associated with handling mortality. Soft-shelled crab incidence observed by at-sea-observers was relayed to DFO within 24 hours of landing, plotted on a 2-minute grid and re-broadcast to all members of industry on the web location: http://sites.google.com/site/nssnowcrab/ as well as via email and fax.

Fishers voluntarily avoid fishing within 1.5 nautical miles of the locations that had greater than 20% soft crab in the observed catch. This adaptive fishing protocol allows rapid adjustment of fishing effort, shifting gear away from or altogether avoiding potentially problematic areas and also helping to save time, fuel and other costs. This approach was not adopted in CFA 4X due to the low incidence of soft crab in the catch and the very short season in N-ENS. However, due to high soft-shell incidence in N-ENS in 2007-2008, direct management measures were implemented. These measures now include a spring season, in addition to the traditional summer season, and closure of sub-areas based on observer reports of high soft crab incidence. Finally, the voluntary return to the sea of immature, legal sized crab ("pencil-clawed" crab) was implemented in 2006 for all areas on the SSE to allow these crab to moult to maturity and so maximise the total yield per crab captured and simultaneously the total lifetime reproductive success of these large-sized males.

In 1996, DFO (Gulf Fisheries Centre, Moncton, New Brunswick) and SSE snow crab fishers initiated a Joint Project Agreement to assess SSE snow crab using a fisheries-independent trawl survey (Biron et al. 1997). It was officially accepted for use as an assessment tool in 1999. These surveys demonstrated the presence of unexploited crab in the south-eastern areas of the SSE, which subsequently led to large increases in TACs (Tables 2-4), fishing effort, landings and catch rates (Figures 2 to 4) and the addition of new participants. Trawl surveys were formally extended to CFA 4X in 2004.

HISTORY

The snow crab fishery is the second most valuable commercial fishery in Atlantic Canada (http://www.dfo-mpo.gc.ca/stats/commercial/sea-maritimes-eng.htm). The SSE snow crab fishery has been in existence since the early 1970s (Figure 2). The earliest records of landings

were at levels of < 1,000 t, mostly in the near-shore areas of Eastern Nova Scotia (ENS; Figure 3). By 1979, landings rose to 1,500 t subsequent to which the fishery declined substantially in the mid-1980s and was considered a collapsed fishery. Recruitment to the fishery was observed in 1986 and since that time, landings have increased considerably (Figure 3). In 1994, directed fishing for snow crab began in CFA 4X, the southern-most range of distribution which continues at low levels.

Annual TACs increased to a peak in 2002/2003 at 9,113 t in S-ENS and 1,500 t in N-ENS. Approximately 10,000 t of snow crab were landed each year from 2000 to 2004. Thus, the post-1998 period was one of rapid expansion of both the economic importance of the crab fishery and also the spatial extent of their exploitation. In 2004, with persistent low levels of recruitment and a steady decline in fishable biomass estimates, since the early-2000s, a more precautionary exploitation strategy was adopted throughout the SSE. TACs increased in 2009 in S- and N-ENS due to signs of strong recruitment, whereas TACs were maintained at low levels in CFA's 4X due to continued signs of low recruitment and high exploitation (Tables 2-4).

METHODS

The primary driver of the analytical approaches developed for the assessment of snow on the SSE is the high temporal and spatial variability in spatial distributions of snow crab in this southern-most extreme of their distributional range in the northwest Atlantic. All data analyses were implemented in the statistical computing language and environment R (R Development Core Team 2009, version 2.10.1) to allow migration and documentation of methods into the future. The complete analytical suite, coded in R, is posted to:

http://sites.google.com/site/autocatalysis/snowcrabanalysis/

A number of spatial and/or temporal interpolation methods are used in this assessment. Thin-plate-splines were computed with Generic Mapping Tools (Wessel and Smith 1998, version 4.1) with a tension parameter T=0.4 and a spatial extent of interpolation of 20 km radius from every datum, a range comparable with that observed in the empirical variograms of many variables (see below). This interpolation method was used only for rapid data visualisation. Geostatistical kriging solutions were computed with the R package, GSTAT (Pebesma 2004, version 0.9-35). For historical temperature data (1950 to present) spatially and temporally constrained Generalized Additive Models were computed with the "mgcv" R-package (Wood 2006; version 1.6-1) at a resolution of 1 km × 1 km and weekly time scales. (See below).

Conversions between cartographic and Cartesian co-ordinate systems for analytical purposes were computed with PROJ (Evenden 1995, version 4.4.9) onto the Universal Transverse Mercator grid system (UTM region 20).

Fisheries Data

Catch rates are biased indicators of crab abundance. The spatial and temporal distribution of both crabs and the fishing effort are not uniform, varying strongly with season, bottom temperatures, food availability, timing of spring plankton blooms, reproductive behaviour, substrate/shelter availability, relative occurrence of soft and immature crab and associated discards, fisher experience, bait type and soak time and ambient currents. Catch rates have not been adjusted for these influences and are presented here only to maintain continuity with historical records.

Mandatory logbooks provide information on location, effort (number of trap hauls) and landings (verified by dockside monitoring). The data are stored in the MARFIS database (Maritimes Region, Policy and Economics Branch, Commercial Data Division). Data were quality checked.

At-sea-observed data provide information about the size structure and the carapace condition of the commercially exploited stock (Table 5, Figure 5). The data are stored in the Observer Database System. At-sea-observers are deployed randomly with the coverage being as evenly distributed as possible between vessels. The target coverage (by quota) was 5% for N-ENS and 10% for S-ENS and 4X. This information was also used to compute the potential by-catch of other non-snow crab species by the snow crab fishery. By-catch estimates of each species *i*, was extrapolated from the biomass of species *i* observed in the catch and the relative observer coverage by:

$$Bycatch_i\,[kg] = Observed\ catch_i\,[kg] \times Total\ snow\ crab\ landings\,[kg] / Observed\ catch_{\ snow\ crab}\,[kg]$$

Research Survey Data

Spatial coverage in the survey is (1) **extensive**, going well beyond all known commercial fishing grounds and (2) **intensive**, with a minimum of one survey station located pseudo-randomly in every 10 × 10 minute area (Figure 6). This sampling design was developed to facilitate geostatistical estimation techniques (i.e., *kriging*; Cressie 1993; Legendre and Legendre 1998; Kern and Coyle 2000). Since 2004, approximately 400 stations have been sampled annually on the fishing vessel, The Gentle Lady, with the same captain. In the 2009 survey, 407 stations were sampled.

The extensiveness of the sampling design allows the objective determination of the spatial bounds of the snow crab population, information that must be known if reliable estimates of biomass and population structure (e.g., size, sex, maturity) are to be made. The spatial distribution of snow crab is quite dynamic and so can rapidly shift to areas where they are not "traditionally" found. For the purposes of monitoring such changes in spatial distribution, sampling is required in areas where crab have not been previously observed. In addition, the distributional patterns of immature, soft-shelled, very old and female crabs do not correspond closely to those of legal size males. The former are considered to be less competitive and more susceptible to predation (Hooper 1986) and usually observed in more marginal environments or substrates with greater cover (gravel, rocks; Comeau et al. 1998). Focusing upon only those areas where large hard-shelled males occur in high frequency would preclude the reliable estimation of the relative abundance of these other important segments of the crab population.

Due to the gradual evolution of the aerial extent and alterations in the intensity and timing of surveys since the mid-1990s, direct inter-annual comparisons of the data are made difficult. Currently, surveys are conducted in the autumn (September to December; i.e., post-fishing season in ENS and just prior to the fishing season in CFA 4X). The timing of the surveys have stabilised to this latter period only since 2002. Prior to 2002, surveys were conducted during the spring/summer (April to July; i.e., prior to the fishing season in ENS). As a consequence, temporal trends are most reliable for the post-2001 period. In the southern-most area of snow crab distribution (CFA 4X) trawl survey coverage has been historically sporadic but have stabilised since 2004.

A *Bigouden Nephrops* trawl, a net originally designed to dig into soft sediments for the capture of lobsters in Europe was used to sample the substrate (headline of 20 m, 27.3 m foot rope mounted with a 3.2 m long 8 mm chain, with a mesh size of 80 mm in the wings and 60 mm in the belly and 40 mm in the cod-end). Net configuration was recorded with Netmind sensors;

depth and temperature were recorded with Minilog sensors; and positional information was recorded with a global positioning system. Tows were conducted for approximately 5 minutes in duration. Actual duration of bottom contact was assessed from Netmind and Minilog data streams. The ship speed was maintained at approximately 2 knots. The warp length was approximately 3 × the depth. Swept area of the net was computed from swept distance and net width.

All crab were enumerated; measured with callipers; shell condition determined (Table 5); claw hardness measured with a durometer; and weighed with motion-compensated scales. The latter allowed direct biomass measurement rather than estimates relying upon allometric relationships between body parts (the approach in 2003 and earlier; see below). Data entry and quality control was provided by JaviTech and migrated onto the Observer Database System, held at DFO, BIO (Bedford Institute of Oceanography, Dartmouth, Nova Scotia).

Snow crab biomass estimates prior to 2004 were approximated from carapace width (CW) measurements by applying an allometric relationship developed for SSE adult hard shelled snow crab (Biron et al. 1999; $R^2 = 0.98$, n = 750):

$$mass\ [g] = 1.543 \times 10^{-4} \times CW\ [mm]^{3.206}$$

The maturity status of males was determined from a combination of biological staging (carapace condition) and morphometric analysis. While physiological maturity is not directly co-incident with the onset of morphometric maturity (morphometrically immature male crabs are more than capable of mating in the absence of competition from terminally moulted males; Sainte-Marie 1993), the latter is more readily quantified. In the terminal moult of male snow crab, a disproportionate increase of chela height (CH) relative to CW is generally observed, a factor which may be associated with increased mating and/or reproductive success. Such morphometrically mature males can be discriminated from those that have not undergone the rapid chela growth via the following equation (E. Wade, personal communication, GFC):

$$M_{(male)} = -25.324\ ln\ (\ CW[mm]\ ) + 19.776\ ln\ (\ CH[mm]\ ) + 56.650$$

where an individual is considered mature if $M_{(male)} > 0$.

The maturity status of females is assessed from direct visual inspection of eggs or gonad development. Where maturity status was ambiguous, maturity was determined morphometrically, as the width of abdomen (measured by the width of the fifth abdominal segment, AW) increases rapidly relative to CW at the onset of morphometric maturity, facilitating the brooding of eggs. This onset of morphometric maturity can be delineated via the following equation (E. Wade, personal communication, GFC):

$$M_{(female)} = -16.423\ ln\ (\ CW[mm]\ ) + 14.756\ \ ln\ (\ CH[mm]\ ) + 14.900$$

where an individual is considered mature if $M_{(female)} > 0$.

Sex ratios were calculated from kriged numerical abundance estimates N as:

$$Sex\ ratio = N_{(female)} / (\ N_{(male)} + N_{(female)}\ )$$

Size-frequency histograms were expressed as number per unit area swept in each size interval ($No \cdot km^{-2}$; i.e., the arithmetic mean numerical density per unit area). Modes and the bounds of the each modal group were identified from size frequency distributions. Each instar (I) was

determined after an analysis of size-frequency distributions to have a lower bound of carapace width (mm) approximated by (see also Figure 7):

$$CW_{(l,\ male)}[mm] = exp\ [\ 1.918 + 0.299\ (\ l - 3\ )\ ]$$

$$CW_{(l,\ female)}[mm] = exp\ [\ 2.199 + 0.315\ (\ l - 4\ )\ ]$$

"*Viable habitat*" for fishable snow crab was modelled from trawl surveys. A binomial Generalised Additive Model with a logit link function was used with smoothed (thin-plate-spline) covariate functions (R-library "mgcv"; Wood 2006). Statistically significant covariates were determined to be year, northing and easting, depth, bottom slope, bottom curvature, bottom temperature, annual amplitude of temperature fluctuations, the week number at which temperature minima were observed, and substrate grain size (Figures 8, 9; Table 6). These modelled relationships were used to predict SSE snow crab habitat after discretising covariate information to a spatial resolution of 1 × 1 km grids (Figure 8). Potential snow crab habitat was identified as those locations where the predicted probability of finding snow crab was > 0.5 (Figure 10). The habitat surface of fishable crab was used as a first approximation for females and immature crab; more appropriate habitat bounds will be determined in the future. The advantage of this approach is that it deviates from the more ad-hoc and contentious approaches towards defining viable snow crab habitat used in the past.

The biomass and numerical densities of crab was predicted upon this dynamically changing habitat surface using geostatistical methods. As such, the approach taken here is akin to a hierarchical modelling approach where presence and absence (0,1) are determined in a primary model and then the non-zero elements are modelled as a secondary model. This prediction involved the modelling of variograms (the behaviour of variance as a function of distance) for each of the individual variables, in each year. The variogram, $2\hat{\gamma}(\Delta x)$ or alternately the quantity, $\hat{\gamma}(\Delta x)$ known as the semi-variance or semi-variogram, is classically determined by the method of moments for some random process, $Z(x)$, such as biomass or number of crab (Cressie 1993). In the simple case of an isotropic random process, $Z(x) = Z(\Delta x)$, where $\Delta x = x_i - x_j$, the distance between all pairwise sampling positions x. For such a processes, the method of moments estimator of the variogram is:

$$\begin{aligned} 2\hat{\gamma}(\Delta x) &= Var(Z(x_i) - Z(x_j)) \\ &= \frac{1}{|N_{\Delta x}|}\sum_{N_{\Delta x}}[Z(x_i + \Delta x) - Z(x_i)]^2 \end{aligned}$$

where Var is the variance, and $N_{\Delta x}$ is the number of pairwise cases.

Empirical variograms standardized to unit variance were constructed using a moving, time-averaged approach. Specifically, a weighted average of the semivariance of 3 years +/- the focal year was obtained where the annual weights decayed exponentially with time (year). The final solution was re-scaled to the local variance of the region and year of interest. Variograms were modelled using a number of functional forms (spherical, exponential, circular) via weighted nonlinear least-squares within GSTAT (Levenberg-Marquart algorithm). A simple least-squares criterion was used to select the best fitting model (examples are provided in Figure 11).

Spatial patterns were modelled as trans-gaussian, Universal (block) Kriging with External Drift (UKED). UKED is a technique that linearly accounts for variations in external (drift) parameters under the kriging formalism (i.e., a variogram constraint). The same covariates that entered the habitat model were used as external drift terms as they were found to be significant factors from preliminary analysis of the abundance density via GLM and GAM. Means and confidence intervals (95%) were established by (Sequential) Conditional Gaussian Simulation (also known as Conditional Posterior Simulation). Conditional Gaussian Simulation is a randomisation approach that robustly captures the variability in the data. However, it does not account for the variability associated with the habitat model and the approach is not completely a hierarchical model. (This will, however, be accomplished in the next assessment).

Growth stanzas of male snow crab were determined from size-frequency analysis (Tables 7, 8) and the numerical abundance of each of these nominal growth stanzas (Figure 12) were also determined via kriging (where possible).

An index of relative exploitation rate (*ER*) at time *t* is calculated as:

$$ER_t = Landings_t / (Landings_t + Mature\ fishable\ biomass_t)$$

where *t* is time, $Landings_t$ is the total landed snow crab in year *t*, and $Mature\ fishable\ biomass_t$ is the total mature and legally fishable biomass (mature male snow crab ≥ 95 mm CW) estimated from kriging for year *t*. This definition is used as there is agreement to focus exploitation upon mature individuals and to return immature crab (pencil-clawed).

An index of relative numerical exploitation rates of each growth stanza was also estimated from at-sea-observed catches for each major area with the assumption of 100% catchability for each growth stanza and constant natural and handling mortality:

$$ER_{(t,i)} = Number\ landed_{(t,i)} / (Number\ landed_{(t,i)} + Number\ surveyed_{(t,i)})$$

where *t* is time, *i* is growth stanza, $Number\ landed_{t,i}$ are the total number of snow crab estimated to have been landed from at-sea-observed proportions of each growth stanza *i* in the catches of year *t*, and $Number\ surveyed_{t,i}$ is the total number of snow crab estimated from kriged numerical abundance of each growth stanza *i*, in year *t*.

Markov-type transition matrices (Tables 9-11) were determined for each nominal growth stanza of male snow crab based upon historical data from 2003 to the present. Data prior to 2003 could not be used to compute the transition matrix due to the very different timing of the surveys (spring) and differences in the spatial extent of the surveys. Due to gear and sampling bias and the bi-annual moulting of snow crab instars 1 to 5, numerical abundance and transition matrix estimates were limited to instars 5 and greater. There is no information on reproduction and early pelagic and benthic survival; nor is there information on any stock-recruitment relationships. As the full life cycle is not being modelled, these transition matrices are referred to as *pseudo-transition matrices*. Further, the relative differences in catchability of the various size and maturity classes were not separated from survivorship resulting in transfer functions that can be greater than 1. The catchability of the commercially exploitable population was assumed to be 100%. These pseudo-transition matrices were developed for each major region separately (N-ENS, S-ENS, CFA 4X) whenever possible and used for forward projection under varying scenarios of exploitation rates.

Forward projection scenarios were derived from fishing patterns in the most recent year of at-sea-observed estimates of relative exploitation for each of the above growth stanzas and the

most recent year of abundance estimates from trawl surveys. Errors ($^{\Delta x}$) from all potential sources were propagated assuming all *n* variables (x_n) were independent of each other:

$$z = f(x_1, x_2, \ldots, x_n)$$
$$(\Delta z)^2 = \left(\frac{\partial f}{\partial x_1}\Delta x_1\right)^2 + \left(\frac{\partial f}{\partial x_2}\Delta x_2\right)^2 + \ldots + \left(\frac{\partial f}{\partial x_n}\Delta x_n\right)^2$$

Ecosystem Indicators

An approach similar to the traffic light framework used in some stock assessments (Brodziak and Link 2002, Koeller et al. 2000, 2006) in combination with a multivariate data simplification method known as ordination (see methods in Choi et al. 2005*b*) was used to describe systemic patterns in temporal data series. Indicators were made directly comparable to one another by expression as anomalies in standard deviation units and then colour-coded. Missing values were coded as white. The metrics were then ordered in the sequence of the primary gradient (first eigenvector) obtained from a multivariate ordination. This allowed the visualisation of any coherence in the manner in which suites of these indicators changed over time. The sequence of the indicators reflects the degree of similarity in their temporal dynamics. Specifically, a variant of Principal Components Analysis (PCA) was used that involved an eigenanalysis of the correlation matrices of the indicators, following data-normalisation of those that were not normally distributed ($\log_{10}(x+1)$ transformations were sufficient). In classical PCA, it is customary to delete all such cases (years) but this would have eliminated much of the data series from the analysis. Instead, Pearson correlation coefficients were computed for all possible pair-wise combinations with the implicit assumption that it represents a first-order approximation of the "true" correlational structure.

PCA was also used to describe the species assemblages that co-occurred with snow crab, derived from the snow crab survey. These co-associations were further analysed with GAMs. Diet information from DFO's groundfish surveys was obtained to determine snow crab predators on the SSE.

LIFE HISTORY

The snow crab (*Chionoecetes opilio*, Brachyura, Majidae, O. Fabricius) is a subarctic species resident along the east coast of North America from northern Labrador to the Gulf of Maine. In the SSE, commercially fished snow crab are generally observed between depths of 60 to 280 m and between temperatures of -1 to 6 °C (Figure 9). Near 7 °C, metabolic costs are thought to match metabolic gains (Foyle et al. 1989). Snow crab are generally observed on soft mud bottoms although small-bodied and moulting crabs are also found on more complex (boulder, cobble) substrates (Sainte-Marie and Hazel 1992; Comeau et al. 1998).

Snow crab eggs are brooded by their mothers for up to 2 years, depending upon ambient temperatures, food availability and the maturity status of the mother (up to 27 months in primiparous females – first breeding event; and up to 24 months in multiparous females – second or possibly third breeding events; Sainte-Marie 1993). More rapid development of eggs (from 12 to 18 months) has been observed in other systems (Elner and Beninger 1995; Webb et al., 2007). A primiparous female of approximately 57.4 mm CW would produce between 35,000 to 46,000 eggs which are extruded between February and April (in the Baie Sainte-Marguerite; Sainte-Marie 1993). The actual range of fecundity is however quite large, especially as multiparous females are thought to be more fecund with more than 100,000 eggs

being produced by each female. Eggs are hatched from April to June when the larvae become pelagic, feeding upon the plankton for 3 to 5 months (zoea stages 1 and 2 and then the megalopea stage). The larvae settle to the bottom in autumn to winter (September to October in the Gulf area). In the SSE, pelagic stages seem to have highest abundance in October and so may begin settling as late as January. Very little is known of survival rates at these early life stages.

Once settled to the bottom (benthic phase), snow crab grow rapidly, moulting approximately twice a year (Sainte-Marie et al. 1995; Comeau et al. 1998). The first inter-moult stage (instar 1) is approximately 3 mm CW. After the 5th instar (15 mm CW) the frequency of moults decline, moulting occurring once a year in the spring until they reach a terminal maturity moult. Growth is allometric with weight increasing approximately 250% with each moult (Figure 7; Tables 7, 8). Terminal moult has been observed to occur between the 9th to the 13th instar in males and the 9th to 10th instar in females (see Results). Just prior to the terminal moult, male crab may skip a moult in one year to moult in the next (Conan et al. 1992). Male snow crab generally reach legal size (≥ 95 mm CW) by the 12th instar; however, a variable fraction of instar 11 snow crab are also within legal size. Male instar 12 snow crab represent an age of approximately 9 years since settlement to the bottom and 11 years since egg extrusion. Thereafter, the life expectancy of a male is approximately 5 to 6 years. Up to 10 months are required for the shell to harden (carapace conditions 1 and early 2; Table 5) and up to 1 year for meat yields to be commercially viable. After hardening of the carapace (carapace conditions 3 to 4) the male is able to mate. At the end of the lifespan of a snow crab (carapace condition 5), the shell decalcifies and becomes, often with heavy epibiont growth. In some warm-water environments (e.g., continental slope areas), epibiont growth occurs at an accelerated rate creating some uncertainty in the classification of carapace condition 5 crab.

Females reproducing for the first time (primiparous females) generally begin their moult to maturity at an average size of 60 mm CW and mate while their carapace is still soft (early spring: prior to the fishing season in ENS, and during the fishing season in CFA 4X). A second mating period later in the year (May to June) has also been observed for multiparous females (Hooper 1986). Complex behavioural patterns have also been observed: the male helps the primiparous female moult, protects her from other males and predators and even feeds her (indirectly; Hooper 1986). Pair formation (a mating embrace where the male holds the female) may occur up to 3 weeks prior to the mating event (Hooper 1986). Upon larval release, males have been seen to wave the females about to help disperse the larvae (i.e., prior to a multiparous mating). Females are selective in their mate choice, as is often the case in sexually dimorphic species, and have been seen to die in the process of resisting mating attempts from unsolicited males (Watson 1972; Hooper 1986). Males compete heavily for females and often injure themselves (losing appendages) while contesting over a female. Larger males with larger chela are generally more successful in mating and protecting females from harm.

ECOSYSTEM CONTEXT

Overview

An overview of some relevant social, economic and ecological factors are here provided to form a basis for discussion of the place of snow crab in its ecosystem. Utilizing the same multivariate approach to the statistical summary and synthesis of indicators as in Choi et al. (2005*b*), key environmental (climatic), social, economic and fishery-related indicators were identified and summarized as standardised residuals in Figure 13. Appendix 1 provides a list of these indicators and their sources.

The first axis of variation accounted for 18% of the total variation in the data (Figure 14), and was dominated by the influence of socio-economic indicators of ocean use by humans and associated changes in their relative abundance: landings and landed values of groundfish (declining), invertebrates (increasing), and Oil and Gas exploration and development (increasing). Gross Domestic Product (GDP) associated with the Oil and Gas sector, as well as total Nova Scotia GDP were also influential factors that have also been increasing. Further, PCB levels in Atlantic puffins and grey seals have been declining as has the physiological condition of many groups of fish. However, the total number of shellfish closures have increased with time, as has the amount of seismic activity. Increasing ocean colour and abundance of, diatoms and dinoflagellates and declining abundance of *Calanus finmarchicus* were also influential to the first axis of variation. The temporal differences along this axis of variation indicates that coherent systemic changes of socio-economic and ecological indicators occurred in the early 1990s with some return to historical states evident (Figure 14).

Importantly, temperature-related changes were generally orthogonal (independent) to the above axis of variation (not shown). This second (orthogonal) axis of variation, accounting for 9% of the total variation was strongly associated with the Cold Intermediate Layer temperature and volume, bottom temperatures and variability in bottom temperatures, bottom oxygen concentrations and sea ice coverage.

Anecdotal information from fishers and fishery-based catch rates (Figures 4, 13) suggests that the abundance of snow crab was quite low in the near-shore areas of the SSE, prior to 1980. Increases in catch rates were observed throughout the shelf in the mid-1980s and 1990s in N- and S-ENS, respectively. As commercially exploitable snow crabs require 9 years or more from the time of settlement to reach the legal size of 95 mm CW, their increasing dominance on the shelf must have had their origins as early as the late-1970s and 1980s (N- and S-ENS, respectively). For S-ENS, these time-lines are confounded by the expansion of the fishing grounds towards increasingly offshore areas and the exploitation of previously unexploited crab populations. However most of this expansion was observed in the post-2000 period when TACs and the closely associated landings increased up to 6 fold relative to the TACs and landings of the 1990s and a doubling of fishing effort (Figures 2, 3). The catch rate increases observed in the 1980s and 1990s, were therefore, likely reflecting real increases in snow crab abundance.

The possible causes of this change in abundance can be simplistically broken down into the following categories of explanation: connectivity (metapopulation dynamics), environment (habitat), top-down (predation), bottom-up (resource limitation), lateral (competition) and human (complex perturbations). These will be discussed below, in brief.

Connectivity

Connectivity refers to the manner in which various populations are connected to each other via immigration and emigration, also known as metapopulation dynamics. In the case of snow crab, connectivity between populations exists due to two main processes: larval dispersion in the planktonic stages and directed movement during the benthic stage.

1. Larval Dispersion

The potential for hydrodynamic transport of snow crab larvae from the southern Gulf of St. Lawrence to the SSE has been studied by J. Chassé (Ocean Sciences Division, BIO, DFO; pers. comm.). Treating larvae as passive particles, simulations suggested that a large numbers

of larvae can be transported onto the SSE (especially near Sable Bank and in the shallows further west). The possibility of snow crab larvae entering the SSE from the Gulf of St. Lawrence region and the Labrador current cannot be ignored, especially given no genetic differences are found between all Atlantic snow crab populations. Further, planktonic organisms can maintain their position in a single location in even very strong advective conditions via control of vertical migrations. Thus the degree of larval retention on the SSE, while unknown, can be large.

The following observations also suggest that the SSE population may be acting as an autonomously reproducing system:

- The temporal dynamics of the SSE snow crab population is generally out-of-phase with the cycles seen thus far in the Southern Gulf of St. Lawrence. If the SSE was dependent upon the larval drift from the Gulf region, the temporal dynamics of the populations would be in-phase.

- The spatial distribution of Brachyuran larvae (Ichthyoplankton Sampling program in the 1980s; see summary in Choi et al. 2005a, page 14) have been observed to be quite pervasive throughout the SSE with no spatial clines (i.e., no declines in abundance with distance from the Gulf of St. Lawrence area) as one might expect if the source of larvae were solely from the Gulf region.

- A pulse of larval abundance was observed from 1997 to 1999 with peak levels in 1998 (Choi et al. 2005a, page 14). The timing of this pulse is concordant with the growth schedules of the currently expected 'local' recruitment. Approximately 9 years would be required to grow from the zoea stages to instar 11/12, the stages in which snow crab begin to moult to maturity in 2007, the same time difference between 1998 and 2007.

- The period in the late 1990s when high larval production was observed was precisely the same period in which the abundance of mature males and females on the SSE were at their peak.

The above *circumstantial evidence* suggests that the snow crab resident on the SSE may be able to function as a self-reproducing system, regardless of inputs from other systems. Even if external sources of larvae do exist, the reproductive potential of the snow crab resident on the SSE proper cannot be dismissed. To this end, the snow crab industry adopted a precautionary approach to the conservation of large mature males (i.e., reduced exploitation rates) to allow them to mate with the more rapidly maturing females in 2006/7.

2. Movement

Spaghetti tags have been applied opportunistically to monitor snow crab movement since the early 1990s (Table 12). Movement information was primarily limited to single recaptures of mature, terminally moulted male crab as crab cannot survive a moult once a tag is applied and tag returns are from the male-only snow crab fishery. The movement of immature and female crab is not known and is a source of uncertainty.

Since 2004, 5,426 tags have been applied and a total of 442 tags (8.1%) have been recaptured and reported. The majority (approximately 75%) of the snow crab tagged between 2004 and 2008 were recaptured within 14.5 kilometres of their release location (Figures 15 and 16). The average distance travelled was 12.8 km with a maximum distance travelled of 276.1 kilometres. Thus, locomotory capacity can be very large. On a monthly basis, the mean distance travelled

was 2.0 km month^{-1} with a maximum of 53.2 km month^{-1}. These distances are linear distances from mark-recapture and are therefore underestimates as the actual distance travelled by the crab will be greater due to the topographical variations and the meandering nature of most animal movement.

On average, crab tagged between 2004 and 2008 were recaptured in the season following the tagging event (mean time to recapture was 9 months) with no reported returns after more than 2 years. During this 4-year period, movement between N-ENS and S-ENS was seldom observed. However, N-ENS fishers in the Glace Bay Hole have explicitly stated that they would not report tagged crab recaptures, rendering this result uncertain. Indeed, historically, movement between N- and S-ENS have been observed. Connectivity is particularly important for CFA 4X where much of the fishery is conducted on the border with S-ENS. More crab have been tagging in this area.

Environmental Control (Habitat)

Known environmental (*abiotic*) influences upon snow crab include the substrate type, temperature variations, and oxygen concentrations. Altered temperature conditions over extended periods of time have been observed in the SSE (Figures 10, 13, 17). For example, prior to 1986, the shelf was characterised by relatively warm bottom waters, low volume of the cold intermediate layer, and a Gulf Stream frontal position closer to the continental shelf. The post-1986 period transitioned to an environment of cold bottom waters, a high volume of cold-intermediate layer waters, and a Gulf Stream frontal position distant from the shelf. The principal cause of the cold conditions is thought to have been along-shelf advection from both the Gulf of St. Lawrence and southern Newfoundland, and local atmospherically-induced, cooling. In the southwestern areas (Emerald Basin), the offshore warm slope water kept subsurface temperatures relatively warm throughout the 1980s and 1990s, the exception being in 1997-98, when cold Labrador Slope Water moved into the region along the shelf break and flooded the lower layers of the central and south western regions. While this event produced the coldest near-bottom conditions in these shelf regions since the 1960s, its duration was short, lasting about one year.

Juvenile crab (approximately instar 5, or 2 years since settlement) were already present in high numbers in the transitional year of 1986. These crab were therefore the benefactors of environmental amelioration; that is, some other factors(s) had allowed their larval and adolescent numbers to build up to very large level prior to these large environmental changes. What these factors(s) are is not yet fully understood, but the reduction in predation mortality associated with the demise of groundfish is an important hypothesis. Further, it is important to note that bottom temperatures in the distributional centers of snow crab have been increasing consistently since the early 1990s while snow crab continues to dominate the bottom environment in S-ENS, somewhat weakening the validity of the temperature-hypothesis. The orthogonal nature of the second major axis of the ordination of ecosystem indicators which was dominated by climatic indicators suggests that climatic variation may not be the cause of the changes observed in the SSE in the early-1990.

Indeed, the spatial extent of what may be considered potential snow crab habitat in the SSE has been mostly quite stable in the historical record (Figure 10). In N-ENS, the surface area of predicted snow crab habitat has varied between 2 to 6 × 10^3 km^2 (Figure 18) with a return to the historical mean in 2009. For S-ENS, the surface area of potential habitat has varied with similar oscillations, ranging from between 45 to 65 × 10^3 km^2 with a historical maximum in 2009. In CFA 4X, the southern-most limit of the distribution of snow crab, potential habitat has been highly variable, ranging from 2 to 10 × 10^3 km^2, with an historical maximum in 2009 (Figure 18).

Within the area that may be considered potential snow crab habitat, average bottom temperatures were 2.6, 2.9 and 3.9 °C in N-, S-ENS and CFA 4X, respectively (Figure 19). Average bottom temperatures in 2009 were generally lower than the long-term means, especially in CFA 4X. Bottom temperature variations have been in phase throughout the three sub-areas in the historical record.

Top-down Control (Predation)

Top-down influences refer to the *role of predators* in controlling a population (Paine 1966; Tremblay 1997; Worm and Myers 2003). The capacity of predatory groundfish to opportunistically feed upon snow crab (Robichaud et al. 1991), in combination with their numerical dominance prior to the 1990s (Choi et al. 2004, 2005b; Frank et al. 2005), suggests that they may have been an important regulating factor controlling the recruitment of snow crab. For example, snow crab in the size range of 5 to 30 mm CW (with a 7 mm CW mode; that is instars 2 to 7, with instar 7 being strongly selected) were targeted by thorny skate and cod. Soft-shelled males in the size range of 77 to 110 mm CW during the spring moult were also a preferred food item. The demise of these predatory groundfish in the post-1990 period and the resultant release from predation upon the immature and soft-shelled crabs may have been an important determinant of the current rise to dominance of snow crab in the SSE.

Historically, the known predators of snow crab have been, in order of importance: Atlantic halibut (*Hippoglossus hippoglossus*), skates (especially thorny skate, *Raja radiata*), Atlantic cod (*Gadus morhua*), seals, American plaice (*Hippoglossoides platessoides*), squids, and other crabs (Bundy 2004). In particular, Atlantic cod (Figure 20) and thorny skate (Figure 21) have been noted for their high selectivity for snow crab and, therefore, their potential to weaken recruitment to commercial sizes (Bailey 1982; Lilly 1984; Robichaud et al. 1989, 1991). Certainly, in the inshore areas of the Scotian Shelf, the anecdotal information that extremely high densities of these early stage snow crabs are found in lobster traps indicates some degree of habitat overlap with adult lobsters. This suggests that one hypothesis for the current increase in lobster abundance in ENS may in part be related to the food base that the juvenile snow crab represent to lobsters. Predation levels upon small immature crabs are also likely to be on the rise in certain offshore areas. High local densities of these more traditional groundfish are found in areas where small immature crab are found in high densities. However, the trends in abundance and condition of groundfish and gadoids in particular continue to be in an impoverished state (Figure 13).

Seals are considered by fishers to be a potential predator of snow crab and their continued increase in abundance (Figure 13) is a source of concern for many fishers. While they have on occasion been observed with snow crab in their stomachs, it should also be emphasised that the highest concentrations of snow crab are currently found in the immediate vicinity of Sable Island, an area where the abundance of grey seals are extremely high. The actual evidence indicating that seals have a negative influence upon the snow crab population therefore seems to be minimal. In fact, it is quite possible that seals may be having a positive influence by physically importing food and food waste (organic matter) from other more outlying areas to the immediate vicinity of Sable Island and so indirectly "feeding" the snow crab and also removing potential predators of crab (in both early pelagic and benthic stages).

Gut analysis of fish species sampled on the SSE suggests that there are no predators that specialise upon snow crab (Table 13). The fish species found to most frequently prey upon snow crab was the Atlantic wolfish (3.5% of the guts sampled since the year 2000 contained snow crab, n=253 guts). However, as total predation mortality is dependent upon the numerical

abundance of the predator, and as the abundance of Atlantic wolfish and sculpins are generally low, their overall influence upon snow crab mortality will be minimal. The formerly dominant and more generalised groundfish predators likely exerted greater predation mortality upon snow crab than these more specialised predators. Amongst these potential predators of snow crab, only cod, American plaice and Yellowtail flounder are found in co-association with snow crab (Figure 22). A strong negative relationship with snow crab was however only found with wolfish species (Table 14).

Bottom-up Control (Resource Limitation)

Bottom-up influences refer to changes in a population due to resource (food) *availability*. Diet studies and field observations (Hooper 1986; Bundy 2004) indicate that the primary food items of larger (mature) crab are, in order of importance: echinoderms, polychaete worms (*Maldane* sp., *Nereis* sp.) and other worm-like invertebrates, detritus, large zooplankton, shrimps, smaller crabs (Rock crab, *Cancer irroratus*; Toad crab, *Hyas coarctatus;* Lesser toad crab, *Hyas araneus*), ocean quahog (*Artica islandica*), bivalve molluscs (e.g., *Mytilus edulis, Modiolus modiolus*), brittle stars (*Ophiura sarsi, Ophiopholis aculeata*) and sea anemones (*Edwardsia* sp., *Metridium senile*). Smaller crabs primarily feed upon, in order of importance: echinoderms, polychaete worms, large zooplankton, detritus and bivalves (e.g., *Mytilus edulis, Modiolus modiolus, Hiatella arctica*). Recent studies have also demonstrated that cannibalism is also highly prevalent in intermediately sized (morphometrically) mature crabs, especially mature females (Sainte-Marie and Lafrance 2002; Squires and Dawe 2003).

Most of these food items are part of the detrital food web, and so the proliferation of snow crab under the hypothesis of bottom-up control would be indicative of the proliferation of the detrital subsystem (potentially at the expense of the other parts of the shelf ecosystem, including that of the demersals). This hypothesis is consistent with what is known of the current structure of the SSE (Choi et al. 2005b):

- Phytoplankton abundance in the most recent decade (1991-2001) was considerably higher and more variable than in the 1960s and early 1970s. This likely resulted in increased sedimentation of organic matter to the ocean bottom (Choi et al. 2005b; Figure 13).

- The recent proliferation of northern shrimp (*Pandalus borealis*), another detritivore and also a potential food item of snow crab (Figures 13, 23) was co-incident with the rise in abundance of snow crab.

- The demise of the groundfish that would competitively feed upon benthic invertebrates (Figure 13).

Certainly the rapid rate of increase in abundance of snow crab would seem to indicate that resource competition was not a limiting factor (up to the late 1990s).

Near the ocean surface, there has been a trend towards increased ocean colour which is an index of chlorophyll concentrations. Therefore, total primary production may be increasing (in the form of diatoms and dinoflagellates). This is likely enhanced by the reduction in abundance of *Calanus finmarchicus*, an important zooplankton link in the pelagic food web. Whether this elevated primary production reaches the detrital system is not yet known.

Lateral Control (Competition)

Lateral (and internal) influences refers to the *competitive interactions* with groundfish, other crab species, cannibalism and reproduction-induced mortality (direct and indirect). The diet of snow crab overlap in many ways with that of groundfish, thus the demise of groundfish in the late 1980s and early 1990s would have been doubly beneficial to snow crab: reduction in predation pressure and also resource competition. The spatial distribution of snow crab overlaps with that of basket stars, sea cucumbers, sand lance, capelin and Toad Crab. Some of these species may be competitors of snow crab for food and habitat space (Figures 22, 24, 25). A strong negative relationship was not found between snow crab and other by catch species (Table 14), suggestive of little competitive interactions.

Human

The human influence is quite complex mixture of the above controlling influences exerted both directly and indirectly upon snow crab. Directed fishing for snow crab is discussed in the next section (Fishery assessment). Here, other forms of human influences are discussed.

1. By-catch of Snow Crab in Other Fisheries:

The by-catch of snow crab in other fisheries remains an area requiring attention. The spatial distribution of Northern shrimp (*Pandalus borealis*) overlaps with that of snow crab and so represents an industry that requires particular attention. The use of trawls by the shrimp industry is of particular concern as they can cause co-incident damage of snow crab, especially those susceptible to crushing such as crab in newly moulted soft-shelled stages. This is particularly relevant as the relative abundance of soft-shelled crab is expected to remain at high levels for the next 3-4 years. The inshore lobster fishery may also represent a source of juvenile and adult female snow crab mortality in some areas due to their capture in lobster traps and (illegal) use as bait. This has been stated by fishers to be more prevalent in CFA 4X. Additionally, bycatch of snow crab in Danish seines has been reported from flatfish fisheries on the Scotian Shelf.

2. By-catch of Other Species in the Snow Crab Fishery:

At-sea observed estimates of by-catch of other species in the commercial catch of the SSE snow crab fishery can be extrapolated to the entire fleet based on landings and the proportion of landings observed (Tables 15, 16). In ENS, a total of 11,453 t of snow crab were landed in 2009 with associated estimates of by-catch at 1.5 t (0.013% of snow crab landings). CFA 4X shows 2 orders of magnitude higher by-catch rates, with a total estimated by-catch of 4.4 t associated with 229.4 t of snow crab landings (1.9 %).

The low incidence of by-catch in commercial catch of the SSE snow crab fishery can be attributed to:

- Trap design – top entry conical traps excludes many fish species.
- Passive nature of fishing gear as opposed to other gear types such as trawl nets (also increases survival of bycatch discards).
- Large mesh-size of trap nets (at a minimum 5.25" knot to knot).

The majority of by-catch for all areas is composed of other invertebrate species (e.g., Northern Stone Crab and American Lobster) for which higher survival rates can be expected after being released as compared to fin fish discards. In the three year record, observers also reported one leatherback turtle as having been entangled in buoy lines. This turtle was reported to be released with minimal or no damage to the animal. As the possibility of entanglement of this *SARA* (*Species at Risk Act*) species exists, a development of best handling practices requires attention.

3. Oil and Gas Exploration and Development:

The interests of the oil and gas industry to explore and develop areas in the SSE near to, or upstream or even directly over major crab fishing grounds and population centers (both N- and S-ENS) has been identified by numerous fishers as a source of concern. Seismic exploration activities continue in the SSE (Figure 13). The potential effects of these seismic methods of exploration upon vulnerable components of the snow crab population and the uncertainties associated with the long-term effects of drilling and extraction include the following:

- Reproductive females can hold eggs for up to two years. Also, snow crab mating behavior is complex, and the disruption of their mating rituals is particularly likely as the courting/mating period can last up to several weeks. This can modify the reproductive/regenerative capacity of the snow crab resident in the SSE. Damage to eggs and modification of reproductive behavior can have lasting influences upon the population and fishery.

- Soft-shelled crab are particularly sensitive to physical trauma. The are abundant and will continue to be so for at least another 3-4 years.

- Immature snow crab are found in shallower waters. In terms of seismic methods of exploration, the shallower areas are an important area of concern as the magnitude of seismic energy reaching the bottom will be much greater than in offshore applications.

- No information is available for the effects of seismic pressure waves upon the planktonic forms of snow crab. This is particularly important for the megalops which are generally found near areas of rapid water density changes (thermoclines and haloclines). Such areas of rapid density change represent areas where the influence of seismic energy upon biota is extremely uncertain as the nature of the seismic energy can be altered.

- Snow crab are known to jettison legs or die when physically shocked (i.e., dropped onto the deck of a boat). This is an important unknown especially as pressure waves can be amplified and wavelengths of pressure waves altered when moving through media of differing densities (e.g., when they are burrowed in mud).

- Being a very long-lived species, the snow crab is exposed to environmental hazards for up to 16 years (since egg extrusion). As such, simple short-term studies (of a few days duration) do not describe the more difficult questions of long-term, compounded (cumulative) effects of seismic energy and oil and gas exploration and development upon snow crab. This is a very large uncertainty.

- Snow crab are important benthic predators. Bioaccumulation of heavy metals and toxic organic chemicals released from oil and gas development is possible, especially as they are so very long-lived. The potential creation of anoxic conditions from drilling is also of

concern. Any damage to the health of snow crab can be detrimental to the reproductive capacity of the population which in turn can also have economic repercussions.

Substantial sacrifices were made from 2004 to 2006 by snow crab fishers to reduce any risks of damaging the reproductive potential of Scotian Shelf snow crab. In the face of such uncertainties and sacrifice, Hunt Oil completed seismic exploration directly over the Glace Bay Hole (an area of high abundance of commercial crab) and the Sidney Bight (a refuge area for immature and female crab) in November 2005 (Source: http://ns.energyresearch.ca/files/Norval_Collins.pdf). The numerous uncertainties associated with such oil and gas exploration/development activities increases the risk of destabilising the snow crab population in the SSE. Others seismic studies continue on Artimon, Banquereau and the Stone Fence in 2009 and 2010.

4. Socio-Economics:

A coherent change in many socio-economic indicators occurred in the mid-1990s, in the same time frame as the large-scale changes in the Scotian Shelf ecosystem (Figure 13). In general, the demographics of Nova Scotia shifted toward an older population base with the ageing of the "baby-boomers". The total population size has also been increasing over the historical record to approximately 935,000 people in 2007 as well as a trend toward a population with higher levels of education. Nova Scotia's GDP has also been increasing along with the GDP associated with Oil and Gas exploitation and the number of cruise ships visiting Halifax. Amongst the more fishery-related indicators, there has been an increased importance of invertebrate fisheries with the demise of the groundfish in the early-1990s, both in terms of total landings and landed values of the fisheries. The number of shell-fish closures have increased over time. However, the relative importance of fishing to the Nova Scotia GDP and the total number of fish harvesters have both been on the decline. The recent world-wide economic down-turn in 2008/2009 will have lasting influences upon all economic sectors, by creating greater uncertainty for the economic viability of the snow crab fishery.

The fished species have changed greatly since the early 1990s in conjunction with the rapid changes in species dominance structure. Since this time, all groundfish landings have declined, falling from 232 kt to 60 kt. Exceptions include dogfish, haddock and halibut. Similarly, the pelagic fish landings have decreased from 125 kt to 55 kt. It should be noted that tuna landings have increased since the 1990s, and swordfish landings are now on the rise. In contrast, invertebrate landings have increased from 111 kt to 135 kt since the 1990s as has the total landed value for all fisheries combined, increasing from $445 million in 1990 to $847 million in 2003. It has declined since then to $661 ($550 from invertebrates) million due in part to falling prices of seafood in past seasons.

The links between the socio-economic changes observed and the changes in the Scotian Shelf ecosystem are complex and cannot be treated in depth in this forum. However, an important issue to consider is whether alterations in social and economic structure can assist in the continued evolution of a precautionary and ecosystem-based management of a sustainable and viable snow crab fishery. Certainly, transparency in management, communication by science and a unity of voice of fishers with a long-term vision for their resource can definitely assist as has been the experience in S-ENS in the post-2004 period – a success that merits emphasis. Maintaining and fostering these positive determinants of stewardship is *essential* for the continued social, economic and ecological sustainability of this fishery.

FISHERY ASSESSMENT

Effort

In S-ENS, fishing effort (Figure 26) was spatially distributed in a similar manner to 2008. In both CFAs 23 and 24, additional effort was applied in near-shore areas that have seen little effort in recent seasons. Much of the fishing effort in CFA 23 still continued to be focused on the holes found between Misaine and Banquereau banks. There was again a complete absence of effort in the western portion (along the "Eastern Shore") of CFA 24.

In N-ENS, a spring season was introduced in 2008 in an effort to combat increased soft and white crab capture and handling. This season was in addition to the traditional summer season and individual fishers were able to fish during either (or both) seasons. After a successful trial in 2008, the majority of landings (>85%) from N-ENS were caught during the spring season in 2009. The fishing effort was focused on the trench of deep water located along the north-eastern coast of Cape Breton (formerly CFAs 21 and 22 Inside) and along the line between N-ENS and CFA 19 with some effort just south of St. Paul's Island. The distribution of the fishing effort in 2009 was dissimilar to the past two seasons with no effort being focused in the Glace Bay Hole.

In CFA 4X, the fishing effort was similar to the previous season. Fishing effort was somewhat concentrated around Sambro with additional effort applied to the north and west of Roseway Bank.

In 2009, approximately 118,774 traps hauls were applied in S-ENS, an increase of 38% from 2008 (slightly higher than the 30% increase in TAC). In N-ENS, approximately 7,648 trap hauls were applied in 2009, an increase of 9% from 2008 (though the TAC increased by 136%).

In CFA 4X. 8,063 trap hauls were applied during the 2009 season. This was a decrease of 34% with the TAC remaining constant between both seasons.

Landings

The total landings were 10,645 t in S-ENS, an increase of 29% (corresponding to a 30% increase in TAC (Table 2, Figure 3). In N-ENS, landings rose dramatically to 579 t (86% landed in the spring) from 238 t in 2008, with a 136% increase in TAC (Table 3). In CFA 4X, 2008/2009 landings were 229 t (vs. 220 t in 2007/2008; Table 4) with no change in the TAC (230 t). The spatial distribution of landings in S-ENS and CFA 4X were comparable with those observed in the past season (Figure 27). However in N-ENS, no landings were reported from the Glace Bay Hole, an area with high associated landings in the past. This is probably a reflection of the distribution of commercial crab during the spring season as opposed to the traditional summer season.

Catch Rates[1]

In N-ENS, the 2008 catch rates were 75.7 kg trap^{-1}, a 125% increase relative to 2008. N-ENS catch rates are above the 13 year mean (55.4 kg trap^{-1}; Figure 4; Table 2) for the first time in 5 seasons. Catch rates were comparable between the spring and summer fisheries. The former had a higher proportion of legal sized, hard crab in the at-sea-observed records. The spatial

1 Recall the caveats about catch rates being inappropriate indicators of fishable biomass, in the Methods.

distribution of catch rates in N-ENS was uniformly low with the exception of one localized area east of Neils Harbour (Figure 28).

In S-ENS, the 2009 catch rates were 89.6 kg trap^{-1}, a 7% decrease relative to 2008 and equivalent to the 13-year mean of 89.7 kg trap^{-1} (Figure 4; Table 3). In 2008, a return to catch rates being distributed throughout these areas, a more normal historic state, was found as opposed to 2006 and 2007 when the highest catch rates (and landings) were from offshore fishing grounds (Figure 28). High catch rates were widely distributed spatially throughout both CFA 23 and CFA 24 in 2009. Peak levels were found towards the Misaine Bank and Sable Island areas of S-ENS. The lack of very low localised catch rates suggests that fishers were efficiently identifying high abundance locations and therefore avoiding over-depletion of lower abundance areas.

In CFA 4X, the 2008/2009 catch rates were 28.4 kg trap^{-1} (Table 4) an increase of 57% from 2007/2008. The catch rates were marginally higher in the eastern area of CFA 4X (Figure 28) but mostly, uniformly low and generally in the range of the N-ENS catch rates during its most impoverished period (2005-2008). Calculation of longer-term averages in CFA 4X is impossible due to shifts in the gear complement (both size and number of traps used) over the past eight seasons.

At-Sea-Observer Coverage

In N-ENS, the at-sea-observer coverage exceeded the target level of 5% of the TAC, at 14.5% (Figure 5, 29). This increased effort was to monitor the capture of soft crab in the spring and summer seasons. A total of 168 traps were sampled (approximately 2.2% of commercial trap hauls). In S-ENS, 9.8% of the TAC was observed (with a target level of 10%). A total of 2,059 traps (approximately 1.7% of commercial trap hauls) were sampled. In CFA 4X, 8.8 % of the TAC was observed, relative to a target level of 10% and a total of 660 traps were sampled.

The lack of undersize crab in the commercial catch of N-ENS suggests a high mortality or movement of undersize crab in the past season. This was in contrast to the high proportion of undersize crab in N-ENS in 2008 (Figure 29, relative to past years and other CFAs).

Newly Matured Crab (CC1 and CC2)

Entry of new recruits was expected for 2008 and 2009 in all areas. This entry was evident in the at-sea-observed fishery data where increased proportions of CC1 and CC2 crab were observed for legal-sized crab as compared to the years previous to 2007 (Tables 17-19, Figures 29, 30).

In N-ENS, CC1 crab represented 5% of the total catch while CC2 crab represented 4% (Figure 29). This is a substantial reduction from 2008 levels (~30% of landings in spring) and 2007 (no spring landings) The spring season was adopted to reduce fishing intensity in the summer season and also to encourage fishing during the earlier period when newly moulted crab are too weak and soft to move into traps. As expected, landings during the spring fishery had negligible catches of CC1 and CC2 crab. High incidence of soft-shelled crab has been suggested anecdotally as being a result of localised depletion of hard-shelled males and a consequent increased trapability of soft-shelled males due to the lack of competition/inhibition. However, high soft-shelf incidence occurs in both high and low catches (assuming catch rates reflect relative abundance).

Low incidence of soft shell catches were observed in both the spring and summer fisheries in N-ENS. If one assumes no recaptures, this amounts to an additional 34 t (6% of landings) being discarded as soft crab with potentially high handling-associated mortalities. This is a substantial improvement from 49% in 2008 and 111% in 2007. The continuation of spring fishing efforts and the implementation of area closures by DFO FAM during the summer fishery based on observer reports and shorter summer fishing period will likely help to control the potential total mortality of soft shell crab in future seasons. Continuing to monitor the situation and adapt as required is essential into the future to avoid the negative consequences of high soft shell incidence in N-ENS in the past.

In S-ENS, the occurrence of CC1 and CC2 crab in 2008 (16% and 6%, respectively) was comparable to that observed in 2008 (Figure 29). Catches of high soft shell percentage (>20% by count) were widely distributed throughout the fishing grounds in both CFAs 23 and 24 during the 2008 fishery. When extrapolated to the S-ENS TAC, this amounts to a potential additional mortality of 1,711 t (16% of landings), an increase from 2008 when soft crab catches represented 13% of the landings and 9% in 2007. The majority of this increase in 2009 arose from increased soft shell catches in CFA 24 whose catch of soft crab rose to 19% in 2009 from 15% the previous year. This capture and discard of soft crab peaked at ~30% in August of 2009. Voluntary closures of areas showing high incidence of soft crab must be adhered to by all members of the fleet to be effective. Unfortunately, this was not the case in 2008 or 2009. The occurrence of fishing effort earlier in the year may help alleviate such high catches of soft crab as in N-ENS.

In CFA 4X for the 2008/9 season, CC1 and CC2 crab represented a total of 2.5% and 0.3% of the total catch and comparable to those of 2007/2008 (Figure 29). The data from CFA 4X are not directly comparable to ENS as their fishing season is disjunct from that of N- and S-ENS. This winter 4X fishery continues to show negligible levels of soft crab as evidenced by only 0.9% of landings being soft.

Old Crab (CC5)

CC5 crab represented a low proportion of the 2009 at-sea-observed catch in both legal and sub-legal size fractions at 1% or less in all areas (Tables 17-19). Similarly low to undetectable proportions of CC5 crab were observed in the trawl surveys (Tables 20-22).

RESOURCE STATUS

Size Structure

A strong size-class of male crab, first detected in 2003 (30 to 40 mm CW) began entry into fishable sizes by 2007 in S-ENS, 2008 in N-ENS and 2009 in CFA 4X (Figure 31). They continue to grow and propagate throughout the SSE. The presence of small immature snow crab spanning almost all size ranges observed by the survey also suggests that steady recruitment to the fishery will likely continue for at least the next 4-5 years. There is even evidence of a new year-class developing in the 20-40 mm CW that is likely the product of the leading edge of the reproductive females from 2007 to 2008. Unfortunately, this is observed only in S-ENS and CFA 4X but not in N-ENS.

The size frequency distributions of female snow crab indicate that the strong size-classes first detected in 2003 for N-ENS and in 2004 for S-ENS are now mostly sexually mature (Figure 32). Reproductive activity should continue for another 2 to 3 years. However, as there is little to

no female recruitment evident with the exception of the instar 5 crab generated 2 to 3 years previously, another gap in reproductive output is expected at the end of this time frame.

Size frequency distributions in CFA 4X exist in a very erratic state, with the disappearance in 2008 of the incoming immature crab observed in 2006 and 2007 and their re-appearance in 2009. The large temperature fluctuations in the area and the different predator fields associated with the warmer waters in the area likely result in these highly unstable size structures.

Sex Ratios

When the relative number of mature females is high, the possibility of reproductive limitation becomes a conservation issue. This is particularly the case in heavily exploited areas where there is an absence of large mature males able to mate and protect the more rapidly maturing and smaller females. This is observed in the southern Gulf of St. Lawrence, where male limitation is a known issue. Conversely, with very low relative numbers of females (e.g., the extended period observed in the early-2000s throughout the SSE) there is low egg and larval production. What may have caused this extended period of poor reproductive potential in the SSE is not known, especially as this fishery is a male-only fishery. A possible explanation for this may arise from differential predation pressures for males and females as they are spatially segregated in their immature stages and they are also sexually dimorphic. Irrespective of the specific cause, extreme sex ratios represent an unhealthy reproductive state and therefore a long-term conservation issue.

There is a high likelihood that sex ratios will naturally fluctuate over time (Figures 33). This is because female snow crab of a given year-class will mature 2 to 4 years earlier than a male from the same year-class. Females also have a shorter life span. Such natural oscillations will be particularly evident when strong year classes dominate a population, as has been the case of the SSE. In the SSE, the sex ratios of mature snow crab have been oscillating with peaks observed in 1996 and again in 2007 with a major trough in the early 2000s (Figure 33, 34). Currently, sex ratios of mature crab are again declining with the ageing of females.

The sex ratios of immature snow crab (Figures 35) have begun to decline from peak levels in 2004. Currently, they are between 20 to 30% female throughout the shelf region. This reduction is due to the females maturing earlier than males from the same year class. The spatial patterns of the sex ratios are distinct between offshore and inshore areas: immature males are found in greater proportion (blue) in offshore whereas immature females (red) are found in greater proportion towards the inshore areas (Figure 36). This spatial segregation likely exposes the crab to differential predation effects. Inshore females are likely fed upon by inshore fish, other macro-invertebrates (including other female snow crab, other crabs and lobster – immature snow crab have been reportedly caught in large numbers in lobster traps; Sainte-Marie and Lafrance 2002; Squires and Dawe 2003). This pattern would be exacerbated by the sexual dimorphism of snow crab, as males grow to be larger and so escape some of the size-dependent predation to which the smaller females would be exposed.

Primiparous females mate during their moulting period, a period when they are highly vulnerable (Watson 1972; Hooper 1986). If their mate is small and unable to definitively defend against other potential mates, females have been observed to be torn apart during the agonistic behaviour (fighting). When potential mates are small, females have been observed to refuse mating and in the process of refusal are also killed. Thus, an abundance of large males would certainly increase the likelihood of successful reproduction for the new wave of maturing females. Further, in an evolutionary context, if heavy fishing of large males causes increased

mating with early maturing dwarf sized males, a greater selection for such traits would be passed onto future generations, potentially leading to stunted populations (a trend observed in many highly exploited species). This however, is a genetic effect occurring over generational time scales. It is important to note that phenotypic plasticity can accelerate these rates of morphometric change in this adaptive species.

Numerical Abundance[2]

The number of immature females caught in the trawl surveys has been increasing since historical lows in 2002 (N-ENS) and 2003 (S-ENS), reaching historical highs in 2006 (Figure 37). Their numbers have since declined rapidly in N-ENS, mostly due to their entry into the mature segment of the population and the lack of small juvenile crab. However in S-ENS and CFA 4X, their numbers have increased in 2009. Most of the immature females are currently found in very shallow areas near-shore in southern SSE (Figure 38).

In all areas, the numerical abundance of mature females declined after reaching peak levels in 2007 (Figures 39, 40). Most of the mature females are currently located in the inshore areas of the SSE; these were therefore the core areas where larval production occurred in 2006 to 2009.

The numerical abundance estimates of carapace condition 5 crab are close to being undetectable in the SSE by the trawl survey (Tables 20-22).

Fishable Biomass[3]

In N-ENS, the post-fishery fishable biomass of snow crab in 2009 was 1,342 t (with a 95% confidence range of: 946 t to 2,059 t; see Figure 41) – a decrease of 72%, relative to 4,836 t in 2008 (Figure 42).

In S-ENS, the post-fishery fishable biomass of snow crab was estimated to be 66.2×10^3 t (with a 95% confidence range of: 55.7 to 77.2×10^3 t) – an increase of 45% from 45.8×10^3 t in 2008 (Figures 41, 42).

In CFA 4X, the pre-fishery fishable biomass was 1,730 t (with a 95% confidence range of 580 to 5,070 t), relative to 1,180 t in 2008/2009, representing a 47% increase.

Recruitment

The index of recruitment, into the fishable biomass (CC1 and CC2 > 95mm CW) was poor from 2003 to 2007 in N-ENS while in S-ENS recruitment was low from 2004 to 2006. CFA 4X recruitment patterns are erratic (Figure 43). The strongest recruitment to fishable biomass is currently in S-ENS and CFA 4X.

It must be emphasised that as the snow crab survey is conducted in late autumn (since 2002), an unknown and variable proportion of the annual recruitment would have also progressed into the mature fishable biomass; and the catchability of soft-shelled crab is likely reduced due to their behaviour of sheltering in rocky burrows. Thus the recruitment index (Figures 43, 44) is only a partial (and biased) index that is sensitive to annual variations in temperature, food

2 Most categories of snow crab are likely under-estimated as catchability corrections are not applied. Their intended use is therefore solely to compare relative trends over time.
3 Fishable biomass in 2009 is likely over-estimated in CFA 4X and S-ENS caused by the large expansion of cold-bottom conditions in 2009. See section on Environmental Control.

availability and crowding, factors that control the onset of moulting and the speed of shell hardening.

Natural Mortality

Wade et al. (2003) suggested that instantaneous mortality rates for southern Gulf of St. Lawrence snow crab > 95 mm CW are within the range of 0.26 to 0.48. Some preliminary analysis suggests that for early benthic females stages (i.e., unfished), instantaneous mortality may be near 1 (Kuhn and Choi, submitted). Further, based upon diet studies (Bundy 2004; see also section: Top-down Control (Predation)), very few natural predators seem to exist for large snow crabs (i.e., legal sized) in the SSE. This has been particularly the case since the demise of most large-bodied predatory groundfish from the eastern part of the SSE (Figure 13). Other potential mortality factors include: bitter crab disease derived from a parasitic dinoflagellate infection (*Hematodinium sp.)* which was found to be prevalent in the SSE since 2008, seals (near Sable Island; although see arguments to the contrary in Ecosystem considerations, above), soft-shell mortality, unreported landings, by-catch in other fisheries (lobster and other crab traps, long-lining, gill-nets, trawling) and activities associated with exploration and development of oil and gas reserves. Until a longer time-series is accumulated, it would be premature to estimate natural mortality with this data-series.

Fishing Mortality

The harvest rates for N-ENS have historically been in the range of 20% to 50%. In 2009, the harvest rate is estimated to have been 29% of the fishable biomass (95% confidence interval: 22% to 38%), an increase from 5% in 2008 (Figure 45). The low exploitation rate in 2008 was implemented to reduce soft-shell handling. The higher than expected exploitation rate in 2009 (the target rate for 2009 was 20%) was caused by a rapid decline in recruitment to the fishable biomass in 2009. The cause of this rapid decline is currently unknown but is associated with either high mortality or movement away from N-ENS of the snow crab recruiting to fishable sizes.

The harvest rates for S-ENS have historically ranged from 10 to 30% of the fishable biomass (Figure 45). In 2004, exploitation rates were reduced due reproductive/conservation concerns. In 2009, the relative exploitation rate was 14% of the fishable biomass (95% confidence interval: 12% to 16%) a marginal decline from 15% in 2008. Realised exploitation rates are likely higher as not all areas where biomass estimates are provided are utilised (e.g., continental slope areas, inshore areas of CFA 24) and as fishable biomass estimates in general are likely over-estimated in S-ENS (see Methods).

In CFA 4X, harvest rates have historically ranged from 10% to 60% (Figure 45). The 2009/2010 harvest rates were 12% of the fishable biomass. In 2008/2009, the harvest rate was 16% of the fishable biomass (95% confidence interval: 5% to 21%). However, due to the very specific spatial extent of the fishery in area 4X, focussed primarily upon the area near Sambro and Roseway, realized exploitation rates are likely to be higher, since the computed exploitation rates incorporate biomass from throughout the CFA 4X area.

THE PRECAUTIONARY APPROACH

In the context of natural resource management, the precautionary approach (PA) identifies the importance of care in decision making by taking into account uncertainties and avoiding risky decisions. This is because natural ecosystems are intrinsically complex and unexpected things

can and often do happen (e.g., Choi and Patten 2001). The origin of the PA is diffuse but has its first precursor in Rachel Carson's 1962 book, Silent Spring, which caused widespread concern about the use of synthetic pesticides and eventually resulted in the abolition of DDT in many parts of the affluent world. The Stockholm Declaration of the United Nations Conference on the Human Environment (UNCHE 1972) was the first international environmental law recognizing the right to a healthy environment. This was taken a little further by the World Commission on Environment and Development (WCED or the Brundtland Commission's Report, Our Common Future, 1987) which highlighted the need for sustainable development. Subsequently, another conference was undertaken in Rio de Janeiro, Brazil (1992) which attempted to establish international agreements to protect the integrity of the environment while recognising state sovereignty and therefore state responsibility for providing equitable resources for both present and future generations. Sustainable development, public participation in the decision making process (especially youth, indigenous people and women), environmental impact assessments and management in particular of environmental pollution and degradation especially when harmful to human health were key points of agreement.

Many other international agreements were undertaken that re-affirmed these positions: the UN Convention on the Law of the Sea (UNCLOS 1982) that recognized territorial jurisdiction with a pollution focus in the EEZ; the FAO (1995) Code of Conduct for Responsible Fisheries emphasising conservation and the precautionary approach, promoting selective fishing gear and responsible fishing methods; the UN Fishing Agreement (UNFA 2001) dealing with straddling and highly migratory fish stocks; the UN Convention on Biological Diversity which identified Ecosystem-Based Management as a global responsibility; the World Summit on Sustainable Development (WSSD 2002) in Johannesburg reaffirmed the common agreement to "maintain or restore stocks to levels that can produce the maximum sustainable yield with the aim of achieving these goals for depleted stocks on an urgent basis and where possible not later than 2015".

Canada, as a signatory to these international agreements, has a legally binding obligation to manage natural resources using a Precautionary Approach (DFO 2005, 2006; Shelton and Sinclair 2008). Ultimately, a PA means to not risk the long-term sustainability of the resource in focus and the ecosystem in which it is embedded. Fortunately, fostering the long-term sustainability of a natural resource in a fishery context also has the direct consequence of fostering the highest possible catch rates (CPUE) and associated socio-economic benefits of an efficient and vigorous fishery. Fostering the long-term biological and ecological sustainability can, therefore, foster the long-term socio-economic sustainability of the dependent industry.

Implementing a PA to resource management requires the careful consideration of all sources of information relating to the sustainability of both the resource in focus and the ecosystem in which it is embedded: scientific and traditional information and associated uncertainties. A further requirement is a transparent way of synthesising this information to somehow measure the sustainability of the resource. The latter is required in order to provide feedback upon the success or lack thereof of specific management actions. To address this requirement, DFO (2006) suggested the use of spawning stock biomass (SSB) as a measure of "sustainability". High levels of SSB were to be considered "healthy" and low levels "unhealthy". Similarly, in the snow crab fishery, the focus is naturally upon the exploitable component: the "fishable biomass". If the relative abundance of fishable biomass is high, most fishers, fisheries managers and fisheries scientists would consider it to be in a more "sustainable" state, and vice versa.

Unfortunately, this perspective is problematic. High abundance can cause a destabilization and collapse of a population through over-crowding, habitat degradation, disease and other

density-dependent mechanisms. Well known examples include deer on islands that eventually overpopulates and eat themselves to extinction; humans on Easter Island that have over-harvested trees leading to population, societal and ecological collapses; or, the over-dominance of species (monocultures in farms and forests) than results in disease or fire outbreaks and eventually large-scale collapse (Diamond 2005). A high abundance does not necessarily equate to high sustainability. The problem lies with not the metric, but rather the focus upon a single indicator. Sustainability is a multidimensional concept that requires reliance upon a broader set of criteria that describes both the resource status and relationships between the focal resource and the surrounding ecosystem (Choi and Patten 2001).

For example, a sustainable snow crab population requires, *at a minimum*: stable and positive levels of egg production, recruitment and stable and comparable levels of natural mortality and ecosystem structure and function. "Natural mortality" and it's converse, "recruitment" are of course catch-all terms that are actually quite complex, involving age and size structure, sex ratios, genetic diversity and numerous ecosystem-level interactions (e.g., habitat variability, resource availability, predation, contaminant loads, disease prevalence, nutrient regeneration and mixing, carbon flux, control of invasive species). Any rapid change in one or more of these potential determinants of sustainability can undermine the long-term sustainability of snow crab. As all of these factors are variable in time and space, the stock assessment of snow crab in the ESS is highly attentive of these potential determinants of population and ecosystem sustainability.

The primary tools of fishery management are the control of fishing catch and effort. Generally, by reducing catch and effort, stock status and/or ecosystem context is expected to improve. However, the lack of recovery of cod since the cod-moratorium in the early 1990s in Atlantic Canada, suggests that even this universal expectation of fisheries control is more a belief than reality. A more risk-averse management approach would therefore seem to be prudent. For the snow crab fishery, the need for additional precaution is further demanded by the fact that the Scotian Shelf is the southern-most limit of the spatial distribution of snow crab. If environmental fluctuations occur in oceanographic currents and bottom temperatures, this is the area that can be expected to be most significantly influenced by such changes.

Ultimately, a population that is "sustainable" is one that is able to maintain the tenuous balance between the various conflicting demands placed upon it by the ecosystem in which it resides, in addition to the humans that influence or exploit it. The maintenance of this balance operates on many space-time scales and therefore requires adaptability (long-term – evolutionary processes) and resilience (short-term – ecological and population dynamic processes). To increase the chances that fishing practices and management actions will result in a sustainable resource, the fisheries influence must simply be small enough that the ability of a population to maintain this balance (adaptability and resilience) is not overtly disturbed or damaged. This requires that the footprint of the fishery (i.e., magnitude of its influence upon this ability) be small, relative to the biological footprint of the population (i.e., magnitudes of egg production, recruitment, "natural" mortality, and numerous other ecosystem-level processes).

Significantly, as the footprint of a fishery is itself context dependent (i.e., population and ecosystem), the use of fixed biological limit reference points of a single indicator is not at all PA-compliant as they are not sensitive to natural and human-induced alterations in the ecosystem context. To determine appropriate thresholds and reactive/mitigative measures for each ecosystem trait is also untenable due to the sheer size and complexity of the SSE and the longevity of the snow crab. However, relevant indicators are evaluated to at least detect rapid alterations. This information is used qualitatively and quantitatively to provide the context by which the snow crab fishery footprint is assessed. The magnitude of the fishery footprint is

minimised aggressively when greater uncertainty is associated with this context (environmental variability, age and size structure irregularities, etc.). For example, if recruitment is poor or environmental conditions erratic, then a more conservative approach (lower exploitation rate) is adopted. Further, all scientific information is brought forward and deliberated in an open and transparent manner with scientists, managers, fishers, aboriginal groups and various stakeholders, as per the Rio Accord (UNCED 1992).

As the snow crab fishery is a male-only fishery that primarily targets post-reproductive males, it has a built-in protection mechanism for the SSB. With these measures alone, the snow crab fishery goes well beyond DFO's (2006) one-dimensional criterion for PA-compliance. The following additional management measures that are currently implemented in the snow crab fishery attempt to further reduce the footprint of this fishery:

- Reproductive potential maintained:
  - The spawning stock biomass is not harvested (i.e., mature females)
  - "Immature" males are still able to mate (not harvested)
  - Small mature males are able to mate as they will never enter the fishery
  - Mature males are exploited at low levels and mostly after the mating season (spring)

- Immature crab are not harvested:
  - Alleviate potential genetic selection upon early size at maturity
  - Voluntary return to water, area closures

- Soft-shelled are not harvested:
  - Reduce unnecessary fishing mortality of the fishable component
  - Voluntary return to water, area closures
  - Soft-shell protocol to assist fleet movement away from problem areas

- Mature male harvest:
  - Harvest rates of the fishable biomass are amongst the lowest in the NW Atlantic, generally ranging between 10 to 30%

- Fishing refugia:
  - Gully MPA
  - Unfished areas on Continental Slope Edge, CFA 24 inshore

- Indicators of population status are monitored annually and spatially:
  - fishable biomass
  - short-term potential recruitment
  - long-term potential recruitment
  - potential egg production
  - size (age) structure
  - carapace conditions
  - spatial distributions
  - sex ratios
  - prevalence of bitter crab disease

- Indicators of ecosystem status are monitored annually (and spatially where available):
  - bottom habitat space
  - bottom and surface temperature conditions/variability
  - abundance metrics of potential predators
  - abundance metrics of potential prey

- species composition
- taxonomic richness
- size-abundance relationships of the whole community (macrofauna)
- various human pressures (landings of fish, pollution, population size, price)

- Open and transparent consultation and communication of scientific information and stakeholders' observations (fishers, aboriginal groups, NGOs):
  - Incorporation of traditional and fishers' knowledge into assessment approaches
  - Foster self-knowledge and long-term sustainability perspectives / stewardship

- At-sea-observers and 100% dockside monitoring:
  - Reduce illegal fishing

To reiterate, the primary objective of the above management measures attempt to maintain the long-term (adaptability) and short-term (resilience) sustainability of the snow crab population and the fishery that is dependent upon it. It is therefore explicitly PA-compliant.

For the purposes of annual TAC advice, harvest rates suggested that are scaled to the natural turnover rates of the fished component (terminally moulted crab). As they have a longevity of approximately 5 years in this stage, this equates to turnover rates of 1/5 (= 20%) per year. That is, 20% of the fishable biomass is expected to turnover in a year, all else being equal. Exploitation strategies that are larger than this scale will have a larger influence than natural processes. Thus, to maintain medium-term stability of the fishable biomass, harvest rates less than 20% are appropriate. This is especially the case when the population and ecosystem context is uncertain, and harvest rates are advised to be below 20% of the fishable biomass. Conversely, when recruitment expectations are strong and ecosystem considerations stable, harvest strategies greater than 20% are advised. As a result, this has resulted in a practice of a harvest rate in the range of 10-30% of the fishable biomass, depending upon population expectations and ecosystem uncertainty/context.

If, however, the abundance of snow crab declines sufficiently, some triggers in fishery management actions are prudent (DFO 2005). Based on historical decisions, the thresholds of fishable biomass that caused action were near the 40% level of the maximum fishable biomass observed in a given area (Bmax in Figure 46). When fishable biomass is less than this threshold, more precautionary approaches towards harvest rates were deliberated and implemented (NENS: 2005-2008). When the fishable biomass declined to a value less than 30% of the maximum fishable biomass observed in an area, discussions of fishery closures occurred. These same threshold triggers are now proposed as potential landmarks where formally agreed upon management actions may become appropriate. Explicit formalisation of these decision rules are expected in the updated Integrated Fisheries Management Plan (IFMP) for snow crab.

RECOMMENDATIONS

General Remarks

1. High catches of soft-shelled crab will likely continue to be a major issue for the next 3 to 4 years in on the SSE. N-ENS and CFA 4X are now able to manage this due to the timing of fishing season. In S-ENS, this is not the case and timely responses from industry to avoid fishing in areas showing high incidence of soft crab must continue to improve if mortality of recruits is to be averted. In 2010, to encourage rapid avoidance measures, soft-shell maps will

be implemented as interactive Googleearth™ maps which can be found at the following web address: http://sites.google.com/site/nssnowcrab .

2. The longevity of the fishable biomass (i.e., the stabilisation of the fishery) can be improved by fishing solely upon morphometrically mature crab. The arguments for this approach are as follows:

- Fishing mature crab would allow them to mate as the fishing season is post-mating season (in ENS, but not CFA 4X). This has the important result of reducing Darwinian selection for early maturation which is a long-term hazard for any fishery that harvests immature individuals.

- The capture of immature crab ("pencil claws") reduces the longevity of the fishable biomass directly relative to a mature-only fishery. The time difference is 2 to 3 years as immature crab go through a soft- and white shelled phases that exclude them from the fishery. Specifically targeting mature (male) crabs is a more optimal exploitation strategy (CC3 and CC4 crab) in that the fishable biomass is harvested when "ready".

- There is a significantly large weight increase if immature crab are allowed to grow and mature (an increase of 250 to even 400%; Figure 7).

In the 2009 season, much of the fishable biomass will still be composed of immature individuals. Indeed, many of these immature crab will represent the largest-sized individuals in future catches, if allowed to grow. They will contribute to reproduction and still represent high quality crab for the industry. Excessive fishing of this component of the fishable biomass is unwise.

Southern-Eastern Nova Scotia

The long-term, precautionary approach adopted by the S-ENS fishers since 2004 has allowed the S-ENS fishers to position themselves well to benefit from the new entry of recruits into fishable sizes. This is an important consideration, given the current economic woes of the world. With the stronger recruitment pulses entering into the fishable biomass and with large numbers of females having had the opportunity to mate with larger and older males (from 2006 to 2009), the health of the S-ENS stock can be said to be definitely improving, the first signs of which were evident in the instar 5 classes observed in the surveys. The fishable biomass continues to increase with strong and steady recruitment expected for at least the next 4-5 years. There is a strong potential for production for at least the next four years but this strength will be dependent upon how aggressively they are exploited. Maintaining an exploitation rate between 10% and 30% would likely provide the greatest longevity to this fishery. Ensuring the longevity of the fishable biomass is important as in the SSE, recruitment has so far occurred in pulses and not at a constant rate as is the case in the Gulf of St. Lawrence. An increase in TAC is suggested.

Northern-Eastern Nova Scotia

The higher exploitation strategies in N-ENS had pushed the fishable component of the N-ENS snow crab population to historic lows for a number of years. The consequence was collateral damage upon the recruitment via soft-shell mortality. This delayed recovery in the region by several years. The reduced exploitation rate in 2008 had helped this recovery to make it through to the fishable biomass. However, recruitment into the fishable biomass in 2009 was low and resulted in exploitation rates higher than the target of 20%. Exploitation strategies

between 10 and 20% would seem to be prudent for this area. A status quo TAC is suggested until a strong and persistent increase in fishable biomass is observed.

CFA 4X

In CFA 4X, exploitation rates are now in the same range as that in other areas of the SSE. As CFA 4X is the southern-most area of snow crab distribution, existing in more "marginal" environments relative to the "prime" areas of S- and N-ENS, an explicitly precautionary approach towards this fishery is recommended. Further, the lower recruitment and the large inter-annual temperature variations in the area increase the uncertainty associated with this area. These factors are tempered by excellent control of soft-shell capture and the buffering influence of S-ENS via immigration. The fishable biomass in the area has finally shown signs of recovery and even an expansion of the spatial range. Exploitation rates between 10 and 30% may help stabilise the population trajectory into the longer-term. A moderate increase in TAC is recommended.

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REFERENCES

Bailey, R. 1982. Relationship between catches of snow crab, *C. Opilio* (O. Fabricius) and abundance of cod *Gadus morhua* L. in the southwestern Gulf of St. Lawrence. *Proceeding of the International Symposium on the Genus Chionoecetes, Alaska Sea Grant Report,* **82-10**:486–497.

Biron, M., Moriyasu, M., Wade, E., DeGrace, P., Campbell, R., and Hebert, M. 1997. Assessment of the 1996 snow crab (*Chionoecetes opilio*) fishery off eastern Cape Breton, Nova Scotia (CFAs 20 to 24, and 4X). *DFO Canadian Stock Assessment Secretariat Research Document,* **1997/102**.

Biron, M., Wade, E., Moriyasu, M., DeGrace, P., Campbell, R., and Hebert, M. 1999. Assessment of the 1998 snow crab (*Chionoecetes opilio*) fisheries off eastern Nova Scotia (Areas 20 to 24, (and 4X)), Canada. *DFO Canadian Stock Assessment Secretariat Research Document,* **1999/12**.

Brodziak, J., and Link, J. 2002. Ecosystem Management: What is it and how can we do it? *Bulletin of Marine Science,* **70**:589-611.

Bundy, A. 2004. Mass balance models of the eastern Scotian Shelf before and after the cod collapse and other ecosystem changes. *Canadian Technical Report on Fisheries and Aquatic Sciences* **2520**:xii + 193 p.

Choi, J.S., Mazumder, A., and Hansell, R.I.C. 1999. The measure of perturbation in a complicated, thermodynamic world. *Ecological Modelling* **117**, 143-158.

Choi, J.S., and Patten, B.C. 2001. Sustainable development: Lessons from the Paradox of Enrichment. *Journal of Ecosystem Health* **7**, 163-177.

Choi, J., and Zisserson, B. 2007. An assessment of the snow crab resident on the Scotian Shelf in 2006. DFO Canadian Science Advisory Secretariat Research Document. **2007/017**.

Choi, J., Zisserson, B., and Reeves, A. 2005*a*. An assessment of the 2004 snow crab populations resident on the Scotian Shelf (CFAs 20 to 24). DFO Canadian Science Advisory Secretariat Research Document. **2005/028**.

Choi, J.S., Frank, K. T. Petrie, B., and Leggett, W. C. 2005*b*. Integrated assessment of a large marine ecosystem: a case study of the devolution of the eastern Scotian Shelf, Canada. *Oceanography and Marine Biology: An Annual Review,* **43**:47–67.

Choi, J.S., Frank, K.T., Leggett, W.C., and Drinkwater, K. 2004. Transition to an alternate state in a continental shelf ecosystem. *Canadian Journal of Fisheries and Aquatic Sciences,* **61**:505–510.

Comeau, M., Conan, G.Y., Maynou, F., Robichaud, G., Therriault, J.C., and Starr, M. 1998. Growth, spatial distribution, and abundance of benthic stages of the snow crab, *Chionoecetes opilio*, in Bonne Bay, Newfoundland, Canada. *Canadian Journal of Fisheries and Aquatic Sciences,* **55**:262–279.

Conan, G.Y., Comeau, M., and Robichaud, G. 1992. Life history and fishery management of Majid crabs: the case study of the Bonne bay (Newfoundland) *Chionoectes opilio* population. *International Council for the Exploration of the Seas,* **C.M.1992/K**:21–21.

Cressie, N. 1993. *Statistics for spatial data*. Wiley-Interscience.

DFO. 2005. Conference on the Governance of High Seas Fisheries and the United Nations Fish Agreement—Moving from Words to Action. http://www.dfo-mpo.gc.ca/fgc-cgp/index_e.htm

DFO. 2006. A harvest strategy compliant with the precautionary approach. DFO Canadian Science Advisory Secretariat Science Advisory Report. **2006/023**. http://www.dfo-mpo.gc.ca/csas/Csas/status/2006/SAR-AS2006_023_E.pdf

Diamond, J.M. 2005. *Collapse : how societies choose to fail or succeed*. Penguin (New York).

Dufour, R. and Dallaire, J.-P. 2003. Status of snow crab populations in the St. Lawrence Estuary and the Northern Gulf of St. Lawrence from 1999 to 2001. DFO Canadian Science Advisory Secretariat Research Document. **2003/048**.

Elner, R.W., and Bailey, R.F.J. 1986. Differential susceptibility of Atlantic snow crab, *Chionoecetes opilio*, stocks to management. *Canadian Special Publication, Fisheries and Aquatic Sciences,* **92**:335–346.

Elner, R.W., and Beninger, P. 1995. Multiple reproductive strategies in snow crab, *Chionoecetes opilio*: physiological pathways and behavioural plasticity. *Journal of Experimental Marine Biology and Ecology,* **193**:93–112.

Evenden, G.I. 1995. *Cartographic projection procedures for the UNIX environment–A user's manual.* Manual for PROJ 4.4.9.

FAO. 1995. FAO Code of Conduct for Responsible fisheries. Rome, FAO.

Foyle, T., O'Dor, R., and Elner, R. 1989. Energetically defining the thermal limits of the snow crab. *Journal of Experimental Biology,* **145**:371–393.

Frank, K.T., Petrie, B., Choi, J.S., and Leggett, W.C. 2005. Trophic cascades in a formerly cod-dominated ecosystem. *Science,* **308**:1621–1623.

Hooper, R. 1986. A spring breeding migration of the snow crab, *Chionoectes opilio* (O. Fabr.), into shallow water in Newfoundland. *Crustaceana,* **50**:257–264.

Kern, J., and Coyle, K.O. 2000. Global block kriging to estimate biomass from acoustic surveys for zooplankton in the western Aleutian Islands. *Canadian Journal of Fisheries and Aquatic Sciences,* **57**:2112–2121.

Koeller, P., Savard, L., Parsons, D., and Fu, C. 2000b. A precautionary approach to assessment and management of shrimp stocks in the Northwest Atlantic. *Journal of Northwest Atlantic Fisheries Science,* **27**: 235-247.

Koeller, P., Covey, M., and King, M. 2006. An Assessment of the Eastern Scotian Shelf Shrimp Stock and Fishery for 2005 and Outlook for 2006. DFO Canadian Science Advisory Secretariat Research Document. **2006/001**.

Kuhn, P., and Choi, J.S. Submitted. Influence of temperature on embryo developmental cycles and mortality of female *Chionoecetes opilio* (snow crab) on the Scotian Shelf, Canada.

Legendre, L., and Legendre, P. 1998. *Numerical Ecology*, vol. 20, of *Developments in Environmental Modelling*. 3 edition, Elsevier Science B.V., Amsterdam (Netherlands).

Lilly, G. 1984. Predation by Atlantic cod on shrimp and crab off north-eastern Newfoundland in autumn of 1977-82. *International Council for the Exploration of the Seas,* **CM.1984/G**:53.

Paine, R.T. 1966. Food web complexity and species diversity. *The American Naturalist,* **100**:65–75.

Pebesma, E.J. 2004. Multivariable geostatistics in S: the Gstat package. *Computers and Geosciences,* **30**:683–691. R package version 0.9-35. http://www.gstat.org/

R Development Core Team 2008. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing Vienna, Austria. ISBN 3-900051-07-0. http://www.R-project.org/

Robichaud, D. A., Bailey, R.F.J., and Elner, R.W. 1989. Growth and distribution of snow crab, *Chionoecetes opilio*, in the southeastern Gulf of St. Lawrence. *Journal of Shellfish Research,* **8**:13–23.

Robichaud, D.A., Elner, R.W., and Bailey, R.F.J. 1991. Differential selection of crab *Chionoecetes opilio* and *Hyas* spp. as prey by sympatric cod *Gadus morhua* and thorny skate *Raja radiata*. *Fishery Bulletin,* **89**:669–680.

Sainte-Marie, B. 1993. Reproductive cycle and fecundity of primiparous and multiparous female snow crab, *Chionoecetes opilio*, in the Northwest Gulf of Saint Lawrence. *Canadian Journal of Fisheries and Aquatic Sciences,* **50**:2147–2156.

Sainte-Marie, B., and Hazel, F. 1992. Moulting and mating of snow crabs, *Chionoecetes opilio*, in shallow waters of the northwest gulf of st. lawrence. *Canadian Journal of Fisheries and Aquatic Sciences,* **49**:1282–1293.

Sainte-Marie, B., and Lafrance, M. 2002. Growth and survival of recently settled snow crab *Chionoecetes opilio* in relation to intra- and intercohort competition and cannibalism: a laboratory study. *Marine Ecology Progress Series,* **244**:191–203.

Sainte-Marie, B., Raymond, S., and Brethes, J.-C. 1995. Growth and maturation of the benthic stages of male snow crab, *Chionoecetes opilio* (Brachyura: Majidae). *Canadian Journal of Fisheries and Aquatic Sciences,* **52**:903–924.

Shelton , P.A., and Sinclair, A.F. 2008. It's time to sharpen our definition of sustainable fisheries management. *Canadian Journal of Fisheries and Aquatic Sciences*, **65**: 2305–2314.

Squires, H.J., and Dawe, E.G. 2003. Stomach contents of snow crab (*Chionoecetes opilio*, Decapoda, Brachyura from the Northeast Newfoundland Shelf. *Journal of Northwest Atlantic Fisheries Science,* **32**:27–38.

Tremblay, M. 1997. Snow crab (*Chionoecetes opilio*) distribution limits and abundance trends on the Scotian Shelf. *Journal of Northwest Atlantic Fisheries Science,* **21**:7–22.

UNCHE (United Nations Conference on the Human Environment). 1972. Report of the United Nations Conference on the Human Environment in Stockholm. United Nations Environment Programme. http://www.unep.org/Documents.Multilingual/Default.asp?DocumentID=97

UNCED (United Nations Conference on Environment and Development). 1992. Agenda 21, the Rio Declaration on Environment and Development, the Statement of Forest Principles, the United Nations Framework Convention on Climate Change and the United Nations Convention on Biological Diversity. A/CONF.151/26 (Vol. I), United Nations.

UNCLOS (United Nations Convention On The Law Of The Sea), 1982. Agreement relating to the implementation of PART XI of the Convention. http://www.un.org/Depts/los/convention_agreements/texts/unclos/closindx.htm

UNFA 2001. The United Nations Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of December 10, 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks. A/CONF.164/37. http://www.un.org/Depts/los/convention_agreements/convention_overview_fish_stocks.htm

WCED (World Commission on Environment and Development). 1987. Our Common Future, Report of the World Commission on Environment and Development. General Assembly document A/42/427, Development and International Co-operation: Environment. http://www.un-documents.net/wced-ocf.htm

WSSD (World Summit on Sustainable Development). 2002. Report of the World Summit on Sustainable Development Johannesburg, South Africa A/CONF.199/20 http://www.un.org/jsummit/html/documents/summit_docs.html

Venebles, W., and Ripley, B. 2002. *Modern applied statistics with S, 4th ed.* Springer-Verlag.

Wade, E., Surette, T., Apaloo, J., and Moriyasu, M. 2003. Estimation of mean annual natural mortality for adult male snow crab *Chionoecetes opilio* in the southern Gulf of St. Lawrence. DFO Canadian Science Advisory Secretariat Research Document. **2003/017**.

Webb, J.B., Eckert G.L., Shirley, T.C., and Tamone, S.L. 2007. Changes in embryonic development and hatching in *Chionecetes opilio* (Snow Crab) with variation in incubation temperature. *Biological Bulletin,* **213**:67-75.

Watson, J. 1972. Mating behaviour of the spider crab, *Chionoecetes opilio. Journal of the Fisheries Research Board of Canada,* **29**:447–449.

Wessel, P., and Smith, W.H.F. 1998. New, improved version of generic mapping tools released. *EOS Transactions of the American Geophysical Union,* **79**:579–593.

Wood, S. 2006. Generalized additive models: an introduction with R. CRC Texts in Statistical Science Series, Volume 67. Chapman and Hall.

Worm, B., and Myers, R. 2003. Meta-analysis of cod-shrimp interactions reveals top-down control in oceanic food webs. *Ecology,* **84**:162–173.

GLOSSARY

Agonistic – Behavioural term relating to aggression, appeasement and avoidance behaviour that occurs between members of the same species. Agonistic behaviour is a much broader term than "aggression," which simply refers to behaviour patterns which serve to intimidate or damage another.

Anthropogenic – Resulting from the influence of human beings on nature.

Benthic – Occurring on the ocean floor.

Biomass – The abundance of living organisms measured in terms of it's weight, mass, volume or caloric energy.

Brachyura (Infraorder) – Known as "true crabs" of which the snow crab is a member. Brachyurans are characterized by a body that is short, wide, and flat. The abdomen is reduced from a strong swimming muscle (e.g., shrimp) to a simple flap covering reproductive appendages and carry eggs. The uropods, which along with the telson form the tail fan in other decapods, are totally absent. All five pairs of walking legs are generally large with the first pair being chelipeds. The antennae and antennules are greatly reduced and originate before the eye stalks.

CC, Carapace Condition – The condition of the shell of a snow crab. Generally related to the age of the organism and the time since last moult. See Table 6 for more details.

CC1 - Newly moulted crab. The top of carapace is light brown and shiny without surface growth of moss or barnacles. Shell is soft and claw is easily broken.

CC2 - The top of carapace is light brown and less shiny with little to no surface growth of moss or barnacles. Shell is clean but hard.

CC3 - The top of carapace is light brown and not shiny. Some growth of moss or barnacles. Shell is hard.

CC4 - The top of carapace is brown and not shiny. Usually some surface growth of moss or barnacles. Shell is hard with small scars. Underneath is yellow brown.

CC5 - Old crab. Carapace is dark brown with substantially mossy ("dirty") surface. Decalcification (black spots) noticeable often at joints. Shell may be soft.

CW, Carapace width – the distance across the carapace of a snow crab (millimetres)

Chela – pincer-like claw of a crustacean or arachnid.

CFA, Crab fishing area – Refers to an individual management area. On the Scotian Shelf they are from north to south: 20 to 24 and 4X.

Commercial biomass – see Fishable biomass.

CPUE, Catch per unit effort – The amount caught by a single fishing event: such as the weight or number of crab captured by a single trap haul.

Density – The amount (biomass or number) of crab per unit area.

Distribution, spatial – The geographic area in which an organism exists.

Durometer – A calibrated instrument used to measure the hardness of an object (such as a crab shell), scaled from 0 (soft) to 100 (hard). A durometer reading of ≥ 68 has been historically used to determine a hard shelled crab.

Dynamic – Characterized by continuous change or time. Not fixed.

Ecosystem – The whole of a system with all the interactions between parts (living and non-living).

ENS – Eastern Nova Scotia (essentially NAFO statistical divisions 4VW).

ER, Exploitation rate – The ratio of biomass fished relative to their abundance. Historically, the GFC calculated ER(t) = Landings(t) / Fishable biomass (t-1), where t is time or year. The Fishable biomass was of the mature segment of the male population ≥ 95 mm CW, estimated from kriging. In this document, the exploitation rate is calculated as ER(t) = Landings(t) / (Landings(t) + Fishable biomass(t)). This change was made as the the time interval between the end of trawl surveys [Biomass(t-1)] and the beginning of fishing [Landings(t)] was up to 10 months. With the alternate method, this lag is approximately 2 months and so likely more accurate.

Extrapolate – To infer or estimate by extending or projecting known information.

Fishable biomass, FB – The biomass of snow crab exploited by the commercial fishery: male, mature, ≥ 95 mm CW and hard shell condition (Carapace conditions 2 to 5). Note that Carapace condition 2 snow crab do not have optimal meat yields at the time of the fishery. While immature crab ≥ 95 mm CW is part of the biomass that can be legally fished, this component is voluntarily returned to allow greater growth.

Fishing mortality, relative – see Exploitation rate.

IBQ – Individual Boat Quota, the amount of snow crab allowed to be legally removed by an individual fisher in a given area over a given period of time.

Instar – A stage of an organism between moults.

Interpolation – The method of determining unknown values through the use of surrounding known values.

Kriging – A method of interpolation for obtaining statistically unbiased estimates of intrinsic variables (i.e., snow crab biomass density) from a set of neighbouring points with known values, constrained by the relative change in variability of the data as a function of distance.

Larvae – The early, immature form of any animal before the assumption of the mature shape.

Metabolic costs – The amount of energy dispensed by an organism in the process of living (heat, organic compounds, faeces, urea/uric acid, etc.).

Metabolic gains – The amount of energy gained through the intake of food or other energy sources.

Morphometric maturity – Maturity status determined from measurements of body shape and size. Male snow crab claw height increases very rapidly in the adult stage (terminal moult), whereas females' abdominal width increases with maturity. While morphometric maturity generally coincides with physiological maturity, morphometrically immature males are known to be able to fertilize females.

Moult – The act of growing, through the shedding of an organism's current shell.

Multiparous – Females bearing eggs resulting from their second or third breeding event (mating).

Numerical density – The number of snow crab in a given surface area.

Pelagic – Occurring in the water column (not on bottom).

Pencil-clawed crab – Immature crab that are legally exploitable (≥ 95 mm CW) but not yet terminally moulted. The final growth increment is estimated to increase the body weight by approximately 250%.

Physiological maturity – Biologically (functionally) able to reproduce.

Primiparous – Females bearing eggs resulting from their first breeding event (mating).

Recruitment – Snow crab that will enter the fishable biomass in the next fishing season, designates as "R-1".

Sexual dimorphism – When shape and/or size differences exists between sexes of a species.

Soft shell – Carapace condition in which the shell produces a durometer reading of less than 68 durometer units.

Spatial – Relating to space (such as a given geographic region such as the Scotian Shelf).

Substrate – bottom type on which an animal exists (rocks, boulders, mud, sand, etc.).

TAC – Total Allowable Catch, the amount of snow crab allowed to be legally removed in a given area over a given period of time.

Temporal – Relating to time (such as a given period of time).

Terminal moult – Snow crab moulted for a final time once mature. The size of these crab will not increase further.

Variogram – The manner in which the variability of data changes with distance from a given location. Empirical variograms depict the data-derived variation as a function of distance. Theoretical/modelled variograms are fitted curves which are ultimately used by the kriging methodology.

Table 1. Snow crab fishing seasons on the Scotian Shelf in the year 2009.

Area	Season
N-ENS	Apr 15 – May 17 & July 20- Aug 8
S-ENS (CFA 23)	May 1 – Sept 15
CFA 23 (Slope)	April 15, Sept 15
S-ENS (CFA 24)	June 15 – Sept 30 (+ extension to Oct 2)
CFA 24 (Slope)	May 1 – Sept 30
CFA 4X	Nov 1 – March 31 (2010)

Table 2. Summary of snow crab fisheries activity of N-ENS.

Year	Licenses	TAC (t)	Landings (t)	CPUE (kg/trap haul)	Effort (x1000 trap hauls)
1997	74	540	534	23.3	22.9
1998	74	660	657	41.6	15.8
1999	78	900	899	54.8	16.4
2000	79	1,015	1,017	68.3	14.9
2001	80	1,065	1,066	94.3	11.3
2002	80	1,493	1,495	101.0	14.8
2003	80	1,493	1,492	76.8	19.4
2004	79	1,416	1,418	60.6	23.4
2005	78	566	562	30.6	18.4
2006	78	487	486	35.6	13.7
2007	78	244	233	23.6	9.9
2008	78	244	238	33.7	7.0
2009	78	576	579	75.7	7.6

Table 3. Summary of snow crab fisheries activity of S-ENS.

Year	Licenses	TAC (t)	Landings (t)	CPUE (kg/trap haul)	Effort (x1000 trap hauls)
1997	59	1,163	1,157	50.9	22.7
1998	67	1,671	1,558	68.9	22.6
1999	-	2,700	2,700	71.1	38.0
2000	158	8,799	8,701	85.0	102.4
2001	163	9,023	9,048	87.8	103.1
2002	149	9,022	8,891	111.7	79.6
2003	145	9,113	8,836	98.6	89.6
2004	130	8,241	8,022	105.6	76.0
2005	114	6,353	6,407	109.5	58.5
2006	114	4,510	4,486	90.9	49.4
2007	115	4,950	4,942	100.1	49.3
2008	115	8,316	8,253	96.1	85.9
2009	116	10,800	10,645	89.6	118.8

Table 4. Summary of snow crab fisheries activity of CFA 4X. From 1994 to 1996, 4 exploratory permits were active with an average of 10.6 t landed each year. Catch rates and calculated effort are for the large trap compliments only. "Year" indicates the year of the start of the fishing season. The first scientifically determined "TACs" in area 4X was provided in 2005. However, due to the novelty of the scientific approach in the area, this advice has been ignored and higher TACs have been negotiated by industry.

Year	Licenses	TAC (t)	Landings (t)	CPUE (kg/trap haul)	Effort (x1000 trap hauls)
1997/08	4		42		
1998/09	4		70		
1999/2000	4		119		
2000/01	6		213		
2001/02	8	520	376		
2002/03	9	600	221	10.1	21.9
2003/04	9	600	289	12.7	22.8
2004/05	9	600	413	20.3	20.8
2005/06	9	337.6	306	28.6	10.8
2006/07	9	337.6	317	27.7	11.5
2007/08	9	230	220	18.1	12.1
2008/2009	9	230	229	28.4	8.0
2009/2010	9	230	*204		

* As of February 10, 2010, Season still in progress.

Table 5. Snow crab carapace conditions and their description. Hardness is measured by a durometer.

Carapace condition	Category	Hardness	Description	Age after terminal moult (approx)
1	New soft	< 68	claws easily bent, carapace soft, brightly coloured, iridescent, no epibionts	0 - 5 months
2	Clean	variable	claws easily bent, carapace soft, brightly coloured, iridescent, some epibionts	5 months - 1 year
3	Intermediate	> 68	carapace hard, dull brown dorsally, yellow-brown ventrally, no iridescence, shell abrasion, epibionts	8 months - 3 years
4	Old	> 68	carapace hard, very dirty, some decay at leg joints, some epibionts	2 - 5 years
5	Very old	variable	carapace soft, very dirty, extensive decay, extensive epibionts	4 - 6 years

Table 6. Analysis of deviance of fishable snow crab habitat (presence/absence) modeled as a binomial Generalized Additive Model. The "s(.)" indicates a smoothed term. The factors were year (year), mean annual temperature (temperature), annual amplitude of temperature oscillations (tamp.annual), week number of annual temperature minima, easting and northing (plon, plat), substrate grain size (substrate mean), bottom curvature (ddZ) and bottom slope (dZ). The dominant influences were spatial location, temperature, depth, substrate and year, in order of statistical significance.

```
Parametric coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)   1.0615     0.0487    21.8   <2e-16 ***

Approximate significance of smooth terms:
                   edf Ref.df Chi.sq p-value
s(yr)             8.06   8.56  57.54 2.6e-09 ***
s(t)              2.44   2.94  92.71 < 2e-16 ***
s(tamp.annual)    2.75   3.25   2.61  0.5010
s(wmin.annual)    7.39   7.89  31.71 9.6e-05 ***
s(plon,plat)     27.96  28.46 436.82 < 2e-16 ***
s(z)              3.22   3.72  74.55 1.6e-15 ***
s(substrate.mean) 4.36   4.86  63.84 1.6e-12 ***
s(ddZ)            6.83   7.33  20.13  0.0066 **
s(dZ)             6.02   6.52  13.39  0.0495 *

R-sq.(adj) =  0.345   Deviance explained = 30.7%
UBRE score = -0.095993  Scale est. = 1         n = 3877
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Table 7. Mean carapace width of male snow crab instars and life stages obtained from trawl surveys. The stages are immature (imm), immature skip moulters (imm.sm), carapace condition 1 and 2 (CC1to2), carapace condition 3 and 4 (CC3to4) and carapace condition 5 (CC5). The numeric suffix to stage indicates the instar. Thus: CC1to2.9 is carapace condition 1 or 2 of instar 9.

Stage	Mean Carapace Width (cm)			
	N-ENS	S-ENS	CFA 4X	Scotian Shelf
imm.5	15.1	14.8	14.9	14.9
imm.6	20.1	20.0	19.3	20.0
imm.7	27.0	26.8	26.8	26.9
imm.8	35.1	35.6	36.5	35.6
imm.9	47.1	48.3	49.0	48.1
imm.10	64.3	65.2	64.4	65.1
imm.11	88.3	86.8	84.2	87.0
imm.12	107.6	107.7	108.4	107.7
imm.sm.9	50.6	50.4	52.9	50.4
imm.sm.10	67.5	68.2	67.1	68.1
imm.sm.11	89.2	88.1	87.9	88.3
imm.sm.12	109.0	108.4	108.5	108.4
CC1to2.9	46.0	47.6	49.7	47.3
CC1to2.10	66.1	65.9	64.8	66.0
CC1to2.11	88.1	87.2	87.8	87.4
CC1to2.12	113.9	113.9	110.0	114.4
CC1to2.13	137.2	139.1	138.5	138.5
CC3to4.9	50.7	51.2	50.6	50.6
CC3to4.10	68.3	68.1	65.7	68.2
CC3to4.11	89.4	89.9	90.0	89.7
CC3to4.12	112.8	114.0	110.4	113.9
CC3to4.13	138.2	138.1	138.1	138.1
CC5.9	51.9	53.9	52.9	52.9
CC5.10	67.9	69.5	68.8	68.8
CC5.11	87.6	88.5	87.9	87.9
CC5.12	109.1	110.5	112.9	109.9
CC5.13	141.1	141.1	141.1	141.1

Table 8. Mean body mass of male snow crab instars and life stages. The stages are immature (imm), immature skip moulters (imm.sm), carapace condition 1 and 2 (CC1to2), carapace condition 3 and 4 (CC3to4) and carapace condition 5 (CC5). The numeric suffix to stage indicates the instar. Thus: CC1to2.9 is carapace condition 1 or 2 of instar 9.

Stage	Mean Body Mass (g)			
	N-ENS	S-ENS	CFA 4X	Scotian Shelf
imm.5	0.7	0.8	1.9	0.8
imm.6	2.0	2.0	2.6	1.9
imm.7	5.2	5.2	6.4	5.2
imm.8	12.4	14.2	18.8	13.6
imm.9	33.2	38.5	43.0	37.3
imm.10	97.4	105.7	108.6	104.7
imm.11	277.1	265.4	250.0	266.4
imm.12	511.0	512.8	547.0	510.0
imm.sm.9	51.6	50.9	58.1	51.0
imm.sm.10	125.3	129.8	124.1	129.4
imm.sm.11	299.2	288.7	286.2	290.4
imm.sm.12	557.7	545.9	548.2	545.5
CC1to2.9	32.4	37.0	48.9	35.2
CC1to2.10	114.0	113.0	102.3	113.4
CC1to2.11	275.7	261.9	285.4	263.9
CC1to2.12	591.6	585.5	533.1	590.2
CC1to2.13	1036.9	1101.3	1082.2	1082.2
CC3to4.9	51.3	53.3	51.5	51.5
CC3to4.10	130.1	129.4	116.0	129.5
CC3to4.11	301.4	307.4	307.9	305.7
CC3to4.12	618.6	640.4	575.6	637.6
CC3to4.13	1141.1	1139.3	1139.0	1139.0
CC5.9	54.9	61.6	58.2	58.2
CC5.10	126.8	136.9	133.0	133.0
CC5.11	284.3	293.1	287.5	287.5
CC5.12	556.6	579.3	608.7	569.6
CC5.13	1217.6	1217.6	1217.6	1217.6

Table 9. Pseudo-Markov transition matrix used for projections in N-ENS.

Stage(t+1)		Stage(t)																								
			Immature								Immature skip moulters				CC1/2					CC3/4						
			5	6	7	8	9	10	11	12	9	10	11	12	9	10	11	12	13	9	10	11	12	13		
Immature		5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
		6	1.14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
		7	-	1.82	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
		8	-	-	1.88	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
		9	-	-	-	1.43	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
		10	-	-	-	-	1.42	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
		11	-	-	-	-	-	0.93	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
		12	-	-	-	-	-	-	0.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
Immature skip moulters		9	-	-	-	-	0.76	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
		10	-	-	-	-	-	0.63	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
		11	-	-	-	-	-	-	0.53	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
		12	-	-	-	-	-	-	-	1.13	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
CC1/2		9	-	-	-	0.21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
		10	-	-	-	-	0.18	-	-	-	0.26	-	-	-	-	-	-	-	-	-	-	-	-	-		
		11	-	-	-	-	-	0.33	-	-	-	0.28	-	-	-	-	-	-	-	-	-	-	-	-		
		12	-	-	-	-	-	-	0.36	-	-	-	0.36	-	-	-	-	-	-	-	-	-	-	-		
		13	-	-	-	-	-	-	-	-	-	-	-	0.28	-	-	-	-	-	-	-	-	-	-		
CC3/4		9	-	-	-	-	-	-	-	-	-	-	-	-	1.24	-	-	-	-	0.67	-	-	-	-		
		10	-	-	-	-	-	-	-	-	-	-	-	-	-	1.39	-	-	-	-	0.67	-	-	-		
		11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.09	-	-	-	-	0.67	-	-		
		12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.24	-	-	-	-	0.67	-		
		13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.24	-	-	-	-	0.67		
CC5		9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	-	-	-	-		
		10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	-	-	-		
		11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	-	-		
		12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	-		

Table 10. Pseudo-Markov transition matrix used for projections in S-ENS.

Stage(t+1)	Stage(t)	5	6	7	8	9	10	11	12	9	10	11	12	9	10	11	12	13	9	10	11	12	13
		Immature								Immature skip moulters				CC1/2					CC3/4				
Immature	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	6	1.47	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	7	-	1.83	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	8	-	-	1.29	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	9	-	-	-	1.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	10	-	-	-	-	1.87	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	11	-	-	-	-	-	1.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	12	-	-	-	-	-	-	0.36	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Immature skip moulters	9	-	-	-	-	0.56	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	10	-	-	-	-	-	0.32	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	11	-	-	-	-	-	-	0.4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	12	-	-	-	-	-	-	-	0.98	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CC1/2	9	-	-	-	0.11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	10	-	-	-	-	0.1	-	-	-	0.08	-	-	-	-	-	-	-	-	-	-	-	-	-
	11	-	-	-	-	-	0.17	-	-	-	0.11	-	-	-	-	-	-	-	-	-	-	-	-
	12	-	-	-	-	-	-	0.15	-	-	-	0.15	-	-	-	-	-	-	-	-	-	-	-
	13	-	-	-	-	-	-	-	-	-	-	-	0.2	-	-	-	-	-	-	-	-	-	-
CC3/4	9	-	-	-	-	-	-	-	-	-	-	-	-	1.84	-	-	-	0.67	-	-	-	-	-
	10	-	-	-	-	-	-	-	-	-	-	-	-	-	1.42	-	-	-	0.67	-	-	-	-
	11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.23	-	-	-	0.67	-	-	-
	12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.67	-	-
	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.84	-	-	-	-	0.67	-
CC5	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	-	-	-	-	-
	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	-	-	-	-
	11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	-	-	-
	12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	-	-
	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	-

Table 11. Pseudo-Markov transition matrix used for projections in CFA 4X.

Stage(t+1)		Stage(t): Immature 5	6	7	8	9	10	11	12	Immature skip moulters 9	10	11	12	CC1/2 9	10	11	12	13	CC3/4 9	10	11	12	13
Immature	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	6	1.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	7	-	0.86	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	8	-	-	1.38	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	9	-	-	-	1.28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	10	-	-	-	-	1.21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	11	-	-	-	-	-	1.28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	12	-	-	-	-	-	-	0.14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Immature skip moulters	9	-	-	-	-	0.27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	10	-	-	-	-	-	0.13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	11	-	-	-	-	-	-	0.46	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	12	-	-	-	-	-	-	-	0.33	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CC1/2	9	-	-	-	0.03	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	10	-	-	-	-	0.13	-	-	-	0.03	-	-	-	-	-	-	-	-	-	-	-	-	-
	11	-	-	-	-	-	0.06	-	-	-	0.06	-	-	-	-	-	-	-	-	-	-	-	-
	12	-	-	-	-	-	-	0.25	-	-	-	0.25	-	-	-	-	-	-	-	-	-	-	-
	13	-	-	-	-	-	-	-	-	-	-	-	0.03	-	-	-	-	-	-	-	-	-	-
CC3/4	9	-	-	-	-	-	-	-	-	-	-	-	-	1.29	-	-	0.67	-	-	-	-	-	-
	10	-	-	-	-	-	-	-	-	-	-	-	-	-	1.29	-	-	0.67	-	-	-	-	-
	11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.29	-	-	0.67	-	-	-	-
	12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.29	-	-	0.67	-	-	-
	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.67	-	-
CC5	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	-	-	-	0.67	-
	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	-	-	-	-
	11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	-	-	-
	12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	-	-
	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	-

Table 12. Tagging Efforts since 2004.

Year	CFA	Vessels Involved	Tags Applied
2004	23 (Slope)	1	290
	24 (Slope)	1	497
2005	23	1	246
2006	23	2	1637
	24	2	1182
	N-ENS	2	399
2008	N-ENS	2	239
	23	1	267
	24	1	318
	4X	1	155
	Total		**5230**

Table 13. The relative proportion of stomachs sampled that contained snow crab.

	2000	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	***Average***
AMERICAN_PLAICE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.03	0.00	0.23
ATLANTIC_WOLFFISH	1.41	0.00	0.00	0.00	0.00	0.00	0.00	15.38	15.00	3.53
COD(ATLANTIC)	0.38	0.00	0.00	0.00	0.00	0.00	0.99	0.42	0.54	0.26
EELPOUT_NEWFOUNDLAND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.67	1.85
HADDOCK	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.03
HALIBUT(ATLANTIC)	0.94	0.00	0.00	14.29	0.00	0.00	0.00	0.00	0.00	1.69
LONGHORN_SCULPIN	0.00	0.00	0.00	0.00	0.00	0.37	0.00	12.38	1.61	1.60
SEA_RAVEN	0.00	0.00	0.00	0.00	0.00	0.84	0.00	0.00	0.00	0.09
SHORTHORN_SCULPIN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SMOOTHSKATE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.04	0.00	1.45
THORNY_SKATE	0.64	0.00	0.00	0.00	0.00	0.00	0.00	3.51	0.00	0.46
WHITE_HAKE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.84	0.00	0.09

Table 14. Model coefficients from a log-linear model of snow crab densities as a function of by catch species from snow crab surveys. High magnitude negative relationships are highlighted.

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	4.91693	0.45267	10.86	< 2e-16	***
t	-0.26453	0.01645	-16.08	< 2e-16	***
tamp.annual	0.1067	0.0204	5.23	1.80E-07	***
z	0.59177	0.07787	7.6	3.60E-14	***
ddZ	0.03142	0.01847	1.7	0.08904	.
AtlanticCod_10	-0.03659	0.00632	-5.79	7.60E-09	***
Haddock_11	-0.09195	0.0125	-7.36	2.30E-13	***
WhiteHake_12	0.04921	0.01325	3.71	0.00021	***
RedHake_13	-0.09345	0.01874	-4.99	6.40E-07	***
SilverHake_14	0.05379	0.00937	5.74	1.00E-08	***
AtlanticTomcod_17	-0.20444	0.14378	-1.42	0.15512	
Redfishsp_23	-0.0299	0.00679	-4.41	1.10E-05	***
AtlanticHalibut_30	-0.05543	0.03345	-1.66	0.0976	.
TurbotGreenlandHalibut_31	-0.02444	0.01147	-2.13	0.0332	*
AmericanPlaice_40	0.16284	0.0095	17.15	< 2e-16	***
YellowtailFlounder_42	-0.03954	0.00926	-4.27	2.00E-05	***
GulfStreamFlounder_44	-0.04407	0.02561	-1.72	0.08538	.
StripedAtlanticWolffish_50	-0.12097	0.01715	-7.05	2.00E-12	***
SpottedWolffish_51	-0.19052	0.07242	-2.63	0.00855	**
Wolffish_59	-0.20697	0.03009	-6.88	6.80E-12	***
HerringAtlantic_60	0.05849	0.01025	5.71	1.20E-08	***
Capelin_64	0.03881	0.01793	2.16	0.03049	*
AtlanticMackerel_70	-0.09187	0.05293	-1.74	0.08265	.
LongfinHake_112	0.0534	0.02375	2.25	0.02458	*
FourbeardRockling_114	0.06558	0.01372	4.78	1.80E-06	***
GreenlandCod_118	-0.15482	0.09861	-1.57	0.1165	
BrillWindowpane_143	0.14984	0.08054	1.86	0.06288	.
LittleSkate_203	0.11216	0.06543	1.71	0.08659	.
WinterSkate_204	0.05698	0.03178	1.79	0.07303	.
Dogfish_274	-0.08508	0.03472	-2.45	0.01431	*
Sculpinfamily_311	0.04213	0.00747	5.64	1.80E-08	***
MonkfishGoosefishAngler_400	-0.04152	0.01458	-2.85	0.00441	**
MarlinSpikeGrenadier_410	-0.09975	0.02416	-4.13	3.70E-05	***
RoughheadGrenadier_411	-0.20638	0.12918	-1.6	0.1102	
RockGrenadierRoundnose_414	-0.1346	0.02519	-5.34	9.60E-08	***
Seasnails_500	-0.0183	0.01237	-1.48	0.13901	
SandLances_590	0.07383	0.01781	4.15	3.50E-05	***
AmericanSandLance_599	-0.069	0.03514	-1.96	0.04963	*
AmericanEel_600	0.40143	0.25033	1.6	0.10888	
CuskEels_660	0.37352	0.16344	2.29	0.02234	*
AtlanticSauryNeedlefish_720	0.16855	0.09365	1.8	0.07198	.
SeaPotato_1823	-0.13158	0.01194	-11.03	< 2e-16	***
PandalusBorealis_2211	0.04451	0.00671	6.63	3.80E-11	***
PandalusMontagui_2212	-0.03362	0.00955	-3.52	0.00043	***
Argissp_2410	0.26398	0.16661	1.58	0.11318	
Crangonsp_2416	0.07093	0.00968	7.33	2.80E-13	***
JonahCrab_2511	-0.09932	0.01405	-7.07	1.80E-12	***

Signif. codes: 0 '***' 0.00	1 '**' 0	.01 '*' 0.0	5 '.' 0.	1 ' ' 1	

Residual standard error: 1.41 on 4411 degrees of freedom
Multiple R-squared: 0.421, Adjusted R-squared: 0.415
F-statistic: 69.8 on 46 and 4411 DF, p-value: <2e-16

Table 15. By-catch (kg) estimates from the ENS snow crab fishery. The estimates are extrapolated from at-sea-observed by-catch and at-sea-observed biomass of catch [i.e., estimated biomass of bycatch = observed biomass of bycatch species / (observed landings of snow crab / total landings of snow crab)]. The snow crab fishery is very species-specific as by-catch levels are <0.01% of snow crab landings for the past four years. At-sea-observers have noted that three leatherback turtles had been entangled in buoy lines; however, they were all released with little to no visible harm.

Species	2006	2007	2008	2009	Average % of Landings
American Lobster	75	0	65	0	0.001
Jonah Crab	11	0	0	0	0.000
Northern Stone Crab	171	48	32	220	0.002
Redfish	32	12	0	50	0.000
Rock Crab	32	0	0	0	0.000
Sea Cucumber	21	36	0	100	0.001
Sea Urchin	11	0	0	10	0.000
Spotted Wolffish	54	0	0	30	0.000
Striped Wolffish	54	0	32	80	0.001
Thorny Skate	32	0	0	0	0.000
Toad Crab	32	12	11	50	0.000
Atlantic Cod	0	0	0	579	0.001
Plaice	0	0	0	10	0.000
Winter Flounder	0	0	0	20	0.000
Flatfish Sp.	0	0	0	10	0.000
Wolffish Sp.	0	0	0	120	0.000
Greenland Cod	0	0	0	40	0.000
Toad Crab	0	0	0	50	0.000
Hermit Crab	0	0	0	40	0.000
Whelk	0	0	0	50	0.000
Starfish Sp.	0	0	0	50	0.000
Basket Stars	0	0	0	10	0.000
Snow Crab Landings	**4,971,000**	**5,174,000**	**8,491,000**	**11,224,000**	

Table 16. By-catch (kg) estimates from the CFA 4X snow crab fishery. The estimates are extrapolated from at-sea-observed by-catch and at-sea-observer coverage, by biomass [i.e., estimated biomass of bycatch = observed biomass of bycatch species / (observed landings of snow crab / total landings of snow crab)]. Note that the snow crab fishery is in general a highly species-specific fishery with extremely low by-catch of other species. By-catch levels have been at 0.782% of total landings in the past four years, with most by-catch species being other crabs and lobster.

Species	2006	2007	2008	2009	Average % of Landings
Jonah Crab	21	0	0	23	0
Northern Stone Crab	170	26	3393	3823	0.818
Deepsea Red Crab	0	0	56	503	0.061
Sea Raven	0	0	45	0	0.005
Sea Cucumber	0	0	11	0	0.001
Sculpin	0	0	45	0	0.005
American Lobster	149	0	11	11	0.015
Rock Crab	64	0	0	0	0.005
Toad Crab	21	0	45	0	0.007
Snow Crab Landings	**308000**	**319000**	**220000**	**229443**	

Table 17. Carapace condition of crab ≥ 95 mm CW (percent by number) over time for N-ENS from at-sea-observed data.

Year	Carapace Condition				
	1	2	3	4	5
2004	2.5	4.9	72.5	19.8	0.4
2005	18.1	2.1	61.0	18.0	0.8
2006	4.4	9.5	71.6	13.4	1.1
2007	44.0	11.3	36.6	7.4	0.6
2008	28.6	3.2	60.8	6.7	0.7
2009	3.2	2.4	90.2	4.1	0.0

Table 18. Carapace condition of crab ≥ 95 mm CW (percent by number) over time for S-ENS from at-sea-observed data.

Year	Carapace Condition				
	1	2	3	4	5
2004	3.2	3.6	74.5	18.0	0.7
2005	5.9	11.0	68.2	14.3	0.7
2006	6.7	17.4	68.4	7.2	0.3
2007	8.8	15.0	58.4	16.3	1.5
2008	11.9	8.4	66.6	12.8	1.0
2009	14.8	5.0	61.0	16.7	2.5

Table 19. Carapace condition of crab ≥ 95 mm CW (percent by number) over time for CFA 4X from at-sea-observed data.

Year	Carapace Condition				
	1	2	3	4	5
2004/5	0.2	1.8	93.4	4.4	0.1
2005/6	0.1	11.8	85.0	3.2	0.0
2006/7	0.1	0.5	98.0	1.4	0.0
2007/8	1.2	0.1	78.1	20.4	0.2
2008/9	1.1	0.2	56.3	42.4	0.1
2009/10					

Table 20. Carapace condition of crab ≥ 95 mm CW (percent by number) over time for N-ENS from trawl surveys. The transition from a spring to a fall survey occurred in 2002/2003. Crude unadjusted proportions.

Year	Carapace Condition				
	1	2	3	4	5
2003	6.6	18.7	56.3	18.4	0.0
2004	2.0	3.5	51.3	38.7	4.5
2005	5.4	0.0	51.7	32.9	10.1
2006	17.1	9.5	16.2	40.0	17.1
2007	16.2	12.0	63.4	7.0	1.4
2008	38.3	4.1	51.0	6.6	0.0
2009	25.1	17.7	55.4	1.7	0.0

Table 21. Carapace condition of crab ≥ 95 mm CW (percent by number) over time for S-ENS from trawl surveys. The transition from a spring to a fall survey occurred in 2002/2003. Crude unadjusted proportions.

Year	Carapace Condition				
	1	2	3	4	5
2003	30.6	7.4	48.5	12.2	1.4
2004	10.1	12.5	56.1	20.8	0.7
2005	7.8	16.2	60.6	15.1	0.4
2006	14.1	10.6	56.8	17.1	1.4
2007	15.2	46.4	29.7	8.5	0.3
2008	13.2	3.8	69.8	12.8	0.4
2009	18.2	15.2	59.2	7.3	0.2

Table 22. Carapace condition of crab ≥ 95 mm CW (percent by number) over time for CFA 4X from trawl surveys. The transition from a spring to a fall survey occurred in 2002/2003. Crude, unadjusted proportions.

Year	Carapace Condition				
	1	2	3	4	5
2003	14.3	0.0	57.1	28.6	0.0
2004	0.0	0.0	84.2	15.8	0.0
2005	9.3	2.3	86.0	2.3	0.0
2006	1.4	5.7	82.8	8.6	1.4
2007	3.8	13.5	76.9	5.8	0.0
2008	11.3	0.0	80.7	8.1	0.0
2009	8.2	6.6	80.9	4.4	0.0

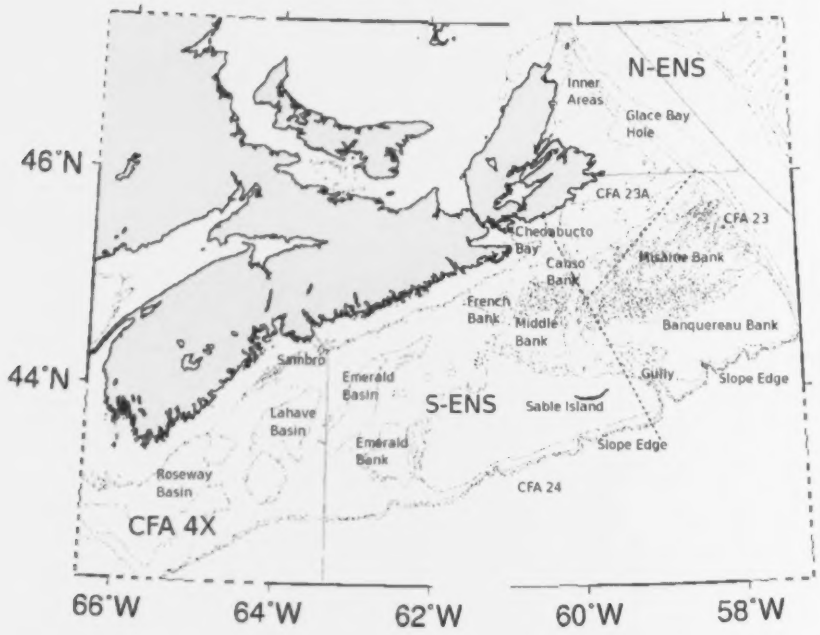


Figure 1. Location of geographic areas and management areas on the Scotian Shelf.

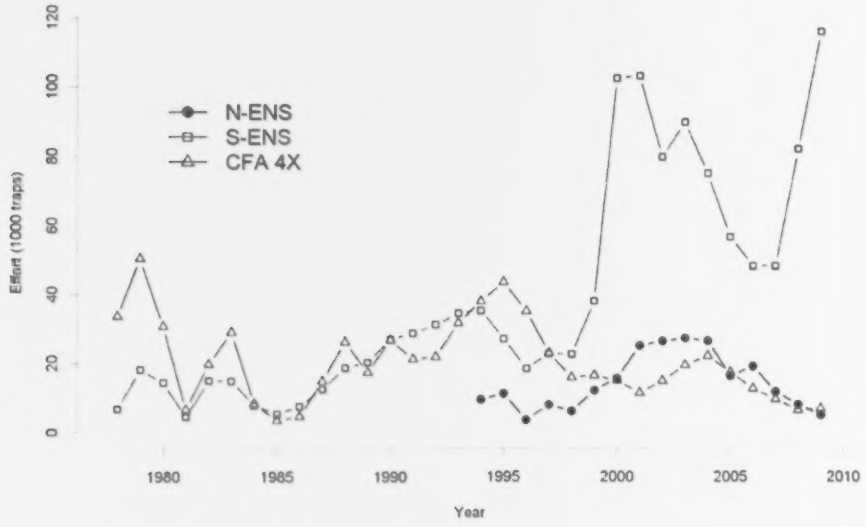


Figure 2. Temporal variations in the fishing effort, expressed as the number of trap hauls. For CFA 4X, year refers to the starting year.

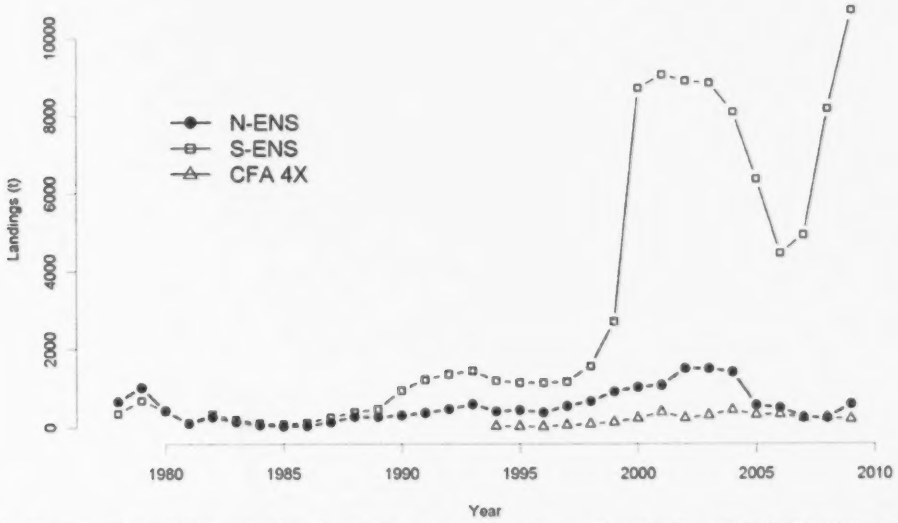


Figure 3. Temporal variations in the landings of snow crab on the Scotian Shelf (t). Note the sharp increase in landings associated with dramatic increases to TACs and a doubling of fishing effort in the year 2000. The landings follow the TACs with little deviation (and so are not shown). For CFA 4X, year refers to the starting year.

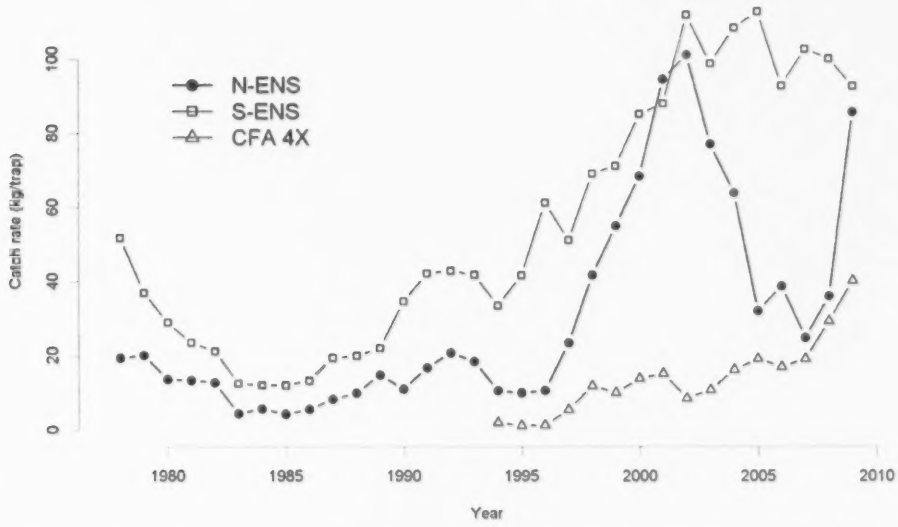


Figure 4. Temporal variations in catch rates of snow crab on the Scotian Shelf, expressed as kg per trap haul. Trap design and size have changed over time. No correction for these varying trap-types nor soak time and bait-type has been attempted (see Methods). For CFA 4X, year refers to the starting year.

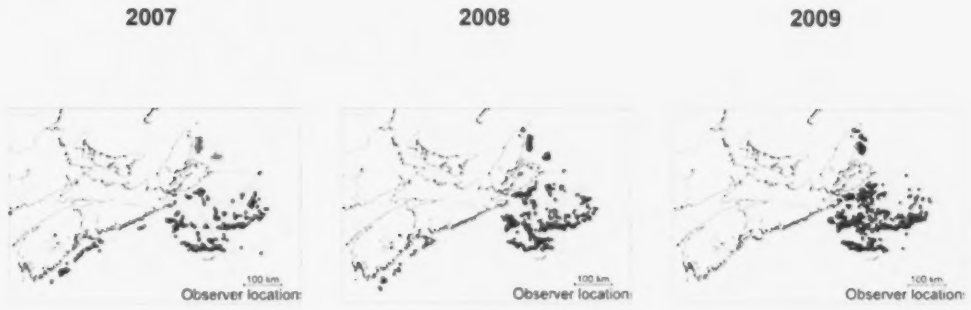


Figure 5. At-sea-observer monitored locations on the Scotian Shelf.

Figure 6. Trawl survey locations on the Scotian Shelf.

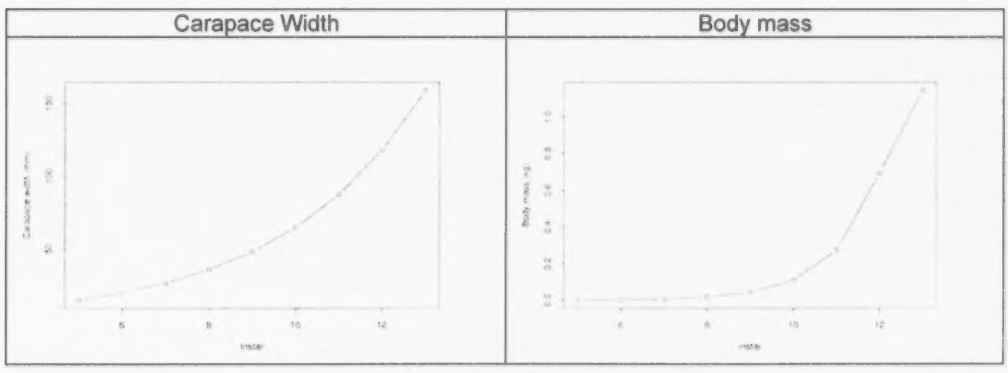


Figure 7. Growth curves determined from Scotian Shelf male snow crab.

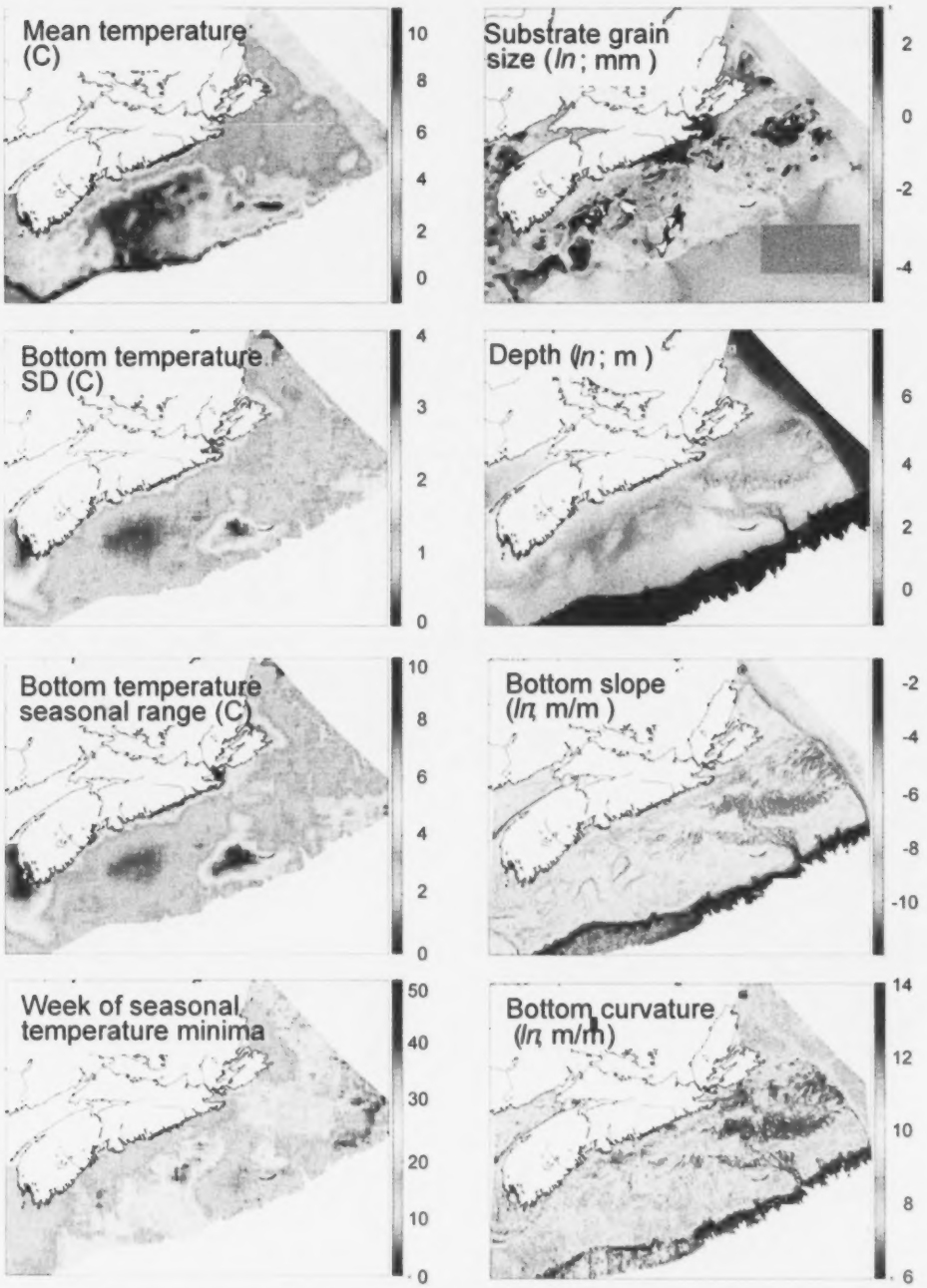


Figure 8. Bottom characteristics used for modelling snow crab habitat delineation. The visualisations of temperature variations are for climatological means. Annual temperature variation estimates were used for modelling.

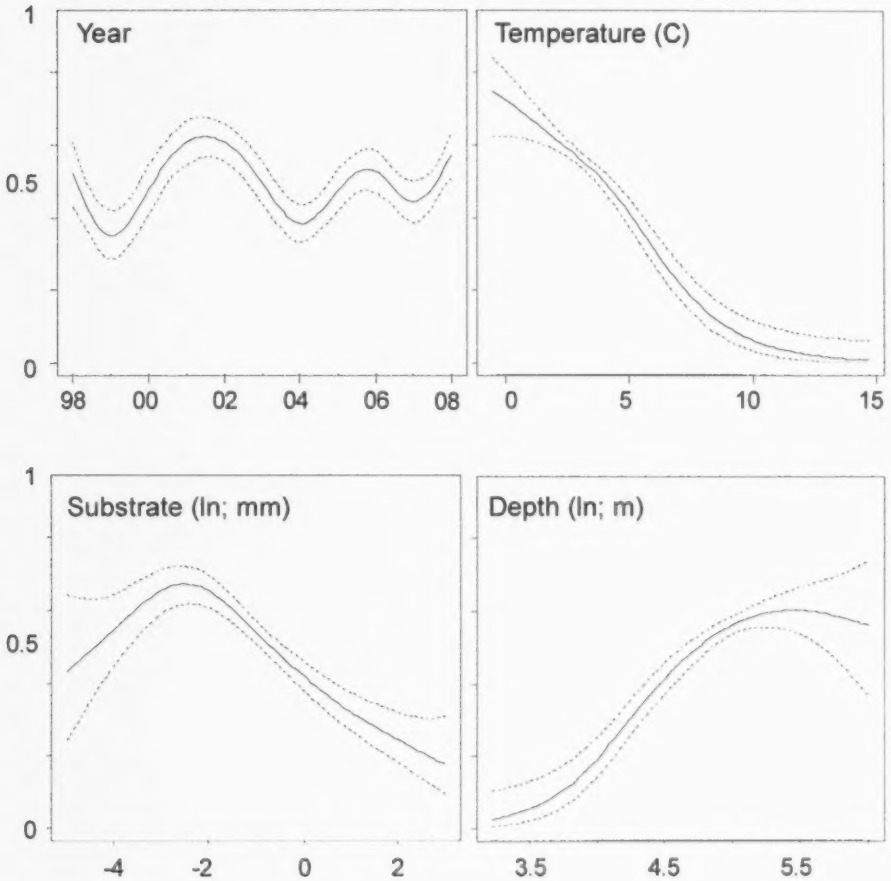


Figure 9. The empirically modeled relationship of snow crab habitat suitability (probability of observing snow crab habitat on the Scotian Shelf) as a function of key environmental key. 95% CI are presented.

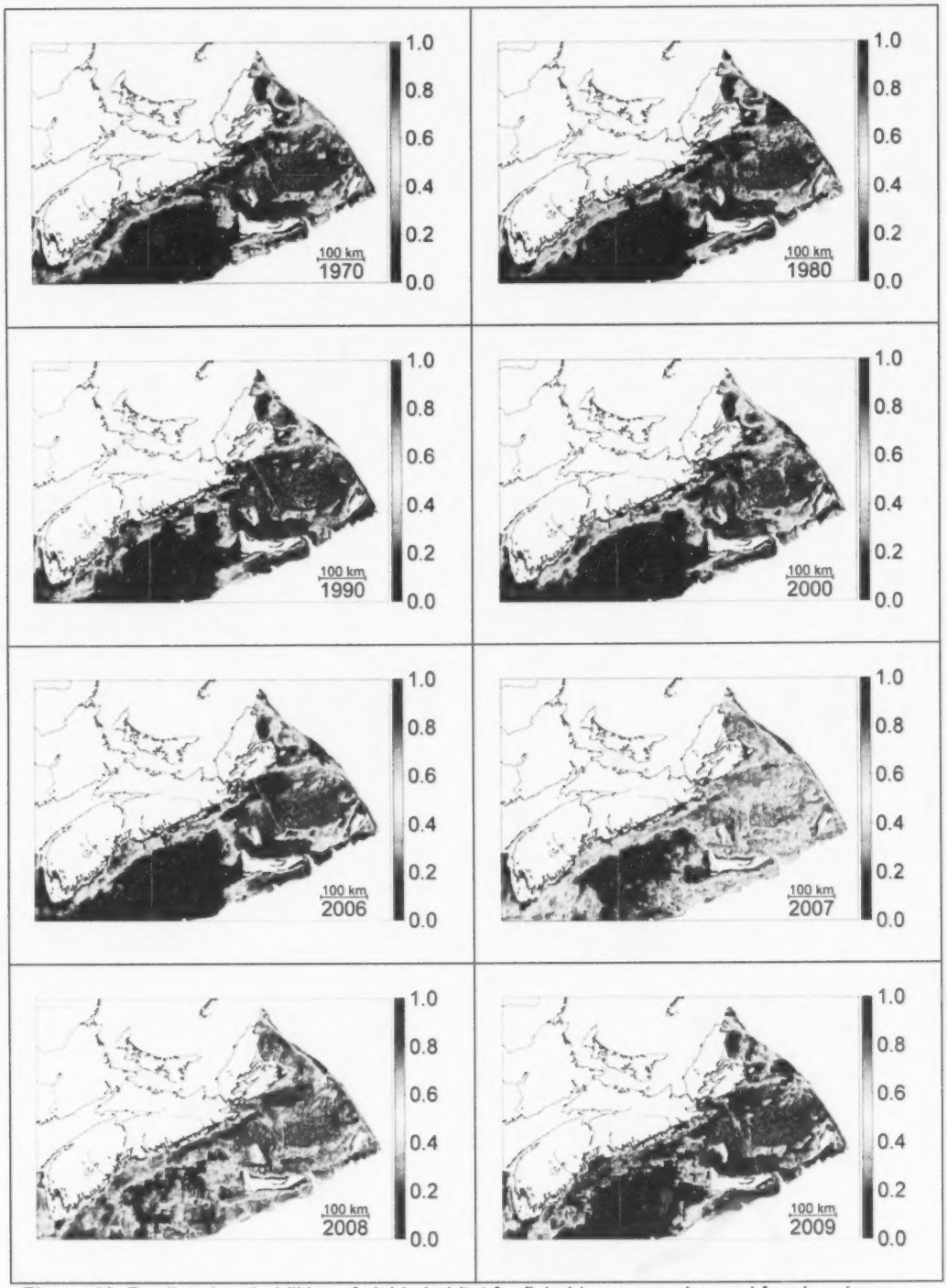


Figure 10. Predicted probabilities of viable habitat for fishable snow crab, used for abundance estimation.

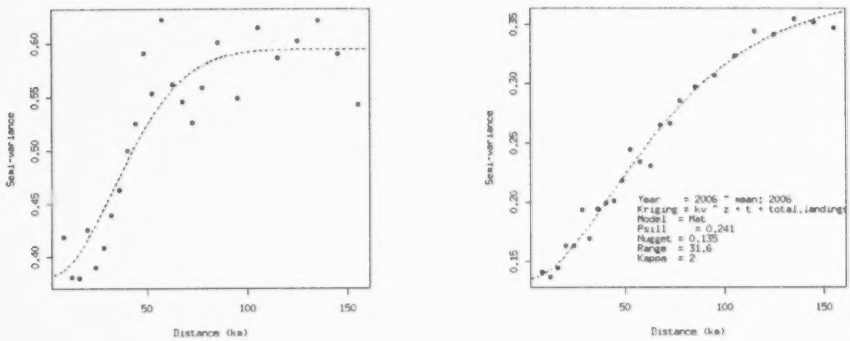


Figure 11. Example variograms of berried females (left) and fishable biomass (right) in 2006, used to constrain the spatial interpolation of snow crab abundance estimates via universal kriging with external drift. Variogram form is more erratic with less abundant categories of crab.

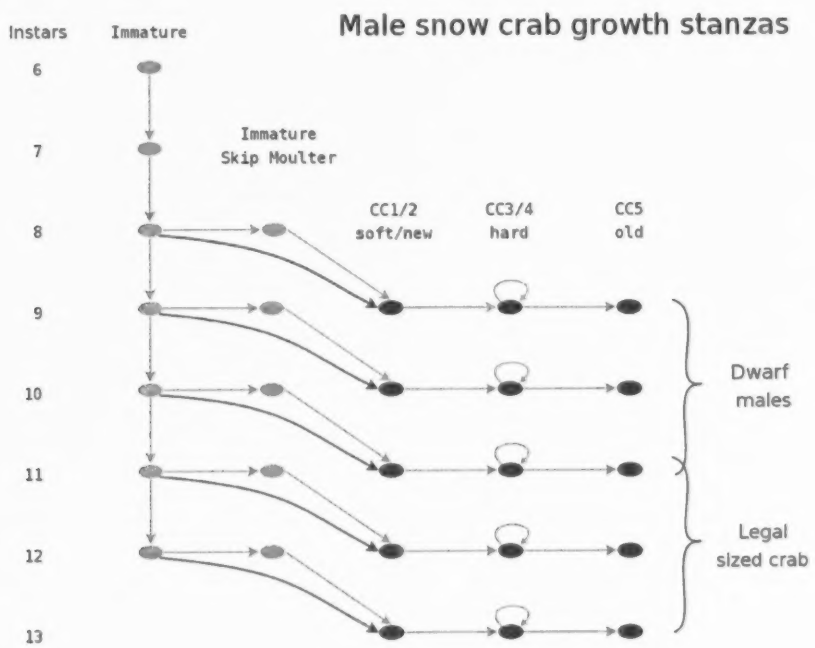
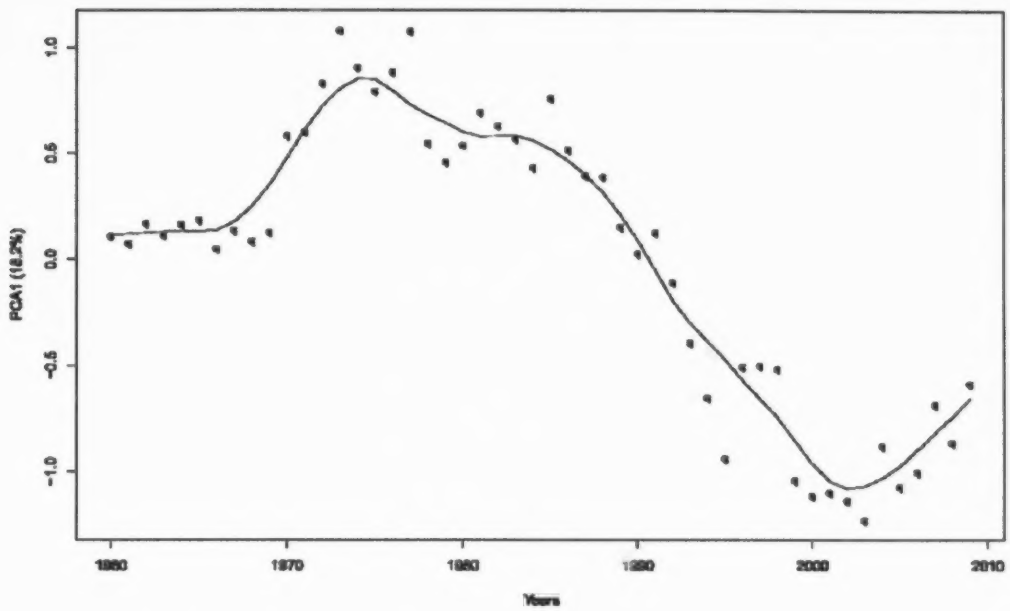


Figure 12. The growth stanzas of male snow crab. Each instar is determined from carapace width bounds obtained from modal analysis and categorized to carapace condition (CC) and maturity from visual inspection and/or maturity equations. Snow crab are resident in each growth stanza for 1 year, with the exception of CC2 to CC4 which are known from mark-recapture studies to last from 2 to 5 years.

Landings: groundfish (0.83, 0.11)
RV: biomass cod (0.79, 0.01)
RV: biomass large demersals (0.74, −0.09)
PCBs: puffins (0.74, −0.48)
RV: condition flatfish (0.71, 0.25)
PCBs: seals (0.7, −0.27)
RV: condition large pelagics (0.68, −0.21)
RV: condition gadoids (0.68, −0.11)
RV: biomass elasmobranchs (0.65, 0.04)
RV: biomass large pelagics (0.65, 0.19)
RV: condition small pelagics (0.63, 0.25)
Landed value: groundfish (0.62, 0.16)
RV: biomass gadoids (0.62, 0)
RV: condition small demersals (0.62, 0.01)
RV: biomass flatfish (0.61, −0.06)
RV: species−area intercept (0.6, 0.04)
CPR: Calanus finmarchicus 5−6 (0.6, −0.62)
CPR: Calanus finmarchicus 1−4 (0.55, −0.56)
Landed value: misc (0.54, −0.13)
Landings: pelagic (0.54, −0.12)
RV: condition large demersals (0.52, 0.26)
GDP: fishing and hunting (0.44, −0.74)
Temperature: SST Halifax (0.33, −0.08)
RV: bottom oxygen (0.33, 0.66)
Employment per total landed value (0.31, −0.52)
Snow crab: mature female abundance (0.25, 0.76)
RV: bottom temperature (0.22, 0.25)
Snow crab: mature male biomass (0.19, 0.21)
Landings: all (0.17, −0.1)
Snow crab: male recruitment (0.16, 0.06)
Gulf stream front: lat@−62 lon (0.15, 0.06)
No. wells drilled (0.14, −0.14)
RV: bottom salinity (0.08, −0.06)
RV: condition elasmobranchs (0.05, 0.44)
Ice coverage (0.04, −0.54)
Landings: misc (−0.04, −0.17)
Snow crab: immature female abundance (−0.05, −0.48)
Seismic 2D; km (−0.09, 0.07)
Shelf front: lat@−62 lon (−0.16, 0.02)
Landed value: pelagics (−0.19, 0.54)
NAO index (−0.19, 0)
GDP: fish processing (−0.24, −0.72)
GDP: oil and gas (−0.24, −1.06)
Snow crab: mature female mean size (−0.3, −0.82)
Snow crab: mature male mean size (−0.37, −1)
No. fish harvesters (−0.41, 0.55)
RV: biomass small demersals (−0.42, 0.01)
GDP: NS total (−0.45, −0.86)
CPR: dinoflagellates (−0.47, 0.48)
Temperature: Sable Is. (−0.51, −0.06)
Seismic 3D, km^2 (−0.55, −0.34)
CPR: colour (−0.59, 0.76)
Shrimp: capelin abundance index (−0.6, 0.64)
NS: % attending university (−0.64, −0.45)
Landed value: all (−0.66, −0.25)
Employment per total landings (−0.67, 0.25)
CPR: diatoms (−0.68, 0.53)
RV: biomass small pelagics (−0.69, 0.37)
RV: biomass capelin (−0.72, 0.53)
Landings: shellfish (−0.76, −0.35)
RV: species−area exponent (−0.77, 0.04)
NS: % 65 and older (−0.79, −0.49)
RV: Shannon index (−0.81, −0.14)
Snow crab: landings (−0.81, −0.57)
Shrimp: abundance index (−0.81, −0.04)
RV: groundfish SMR (−0.83, 0.28)
Landed value: snow crab (−0.86, −0.25)
Landings: snow crab (−0.87, −0.42)
RV: no. taxa predicted at 100 km2 (−0.88, 0.34)
RV: taxonomic richness (100km) (−0.88, 0.35)
Seal abundance adult (−0.95, −0.28)
Landed value: shellfish (−0.98, −0.22)
No. shellfish closures (−0.99, 0.15)
NS: Population size (−1.01, −0.1)
1960
1970
1980
1990
2000
Years

Figure 13. Sorted ordination of anomalies of key social, economic and ecological patterns on the Scotian Shelf relevant to snow crab. Red indicates below the mean and green indicates above the mean.



Figures 14. First axis of variations in ordination of anomalies of social, economic and ecological patterns on the Scotian Shelf. Note strong variability observed near the time of the fishery collapse in the early 1990s. Note strong variability observed near the time of the fishery collapse in the early 1990s.

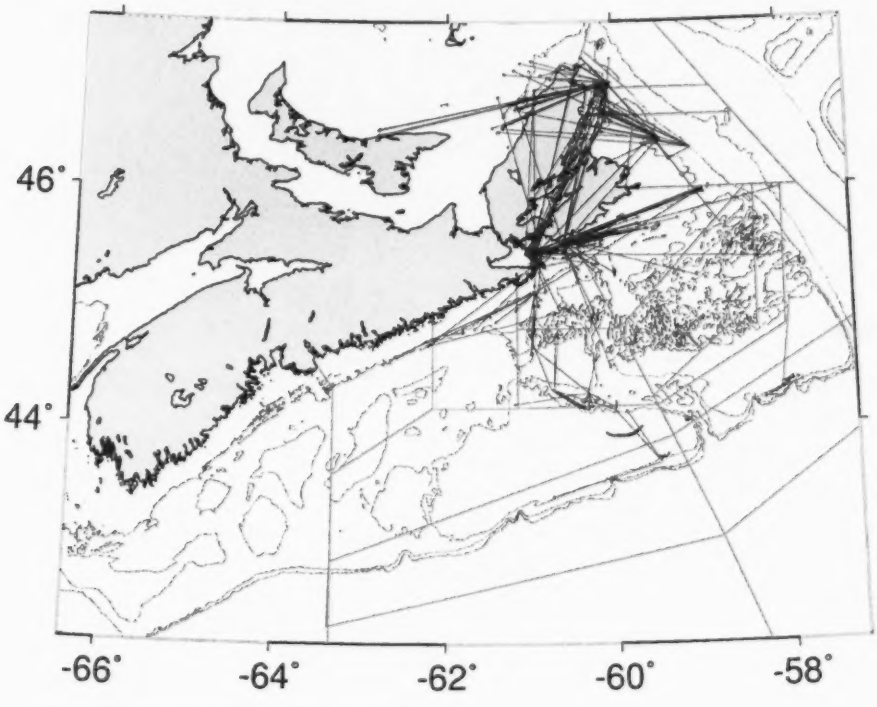


Figure 15. Movement of tagged snow crab.

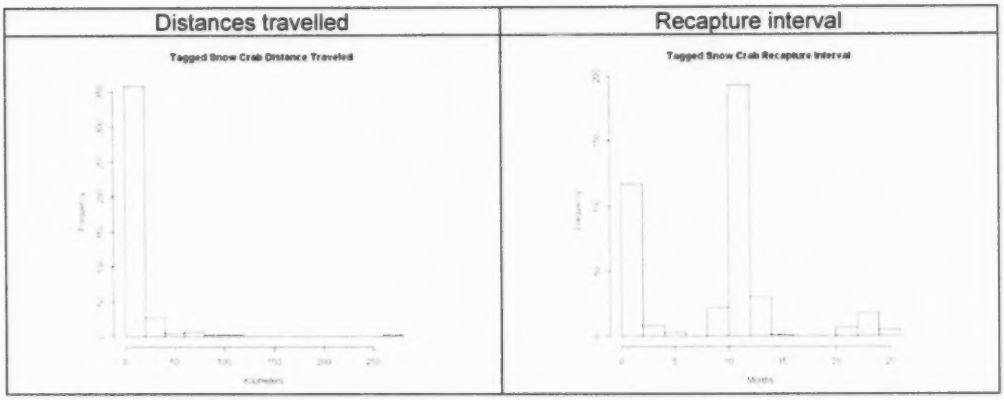


Figure 16. (Left) Distance traveled by Tagged Snow Crab in ENS 2004-2008. (Right) Tagged snow crab in ENS: return interval in months between initial release and first recapture.

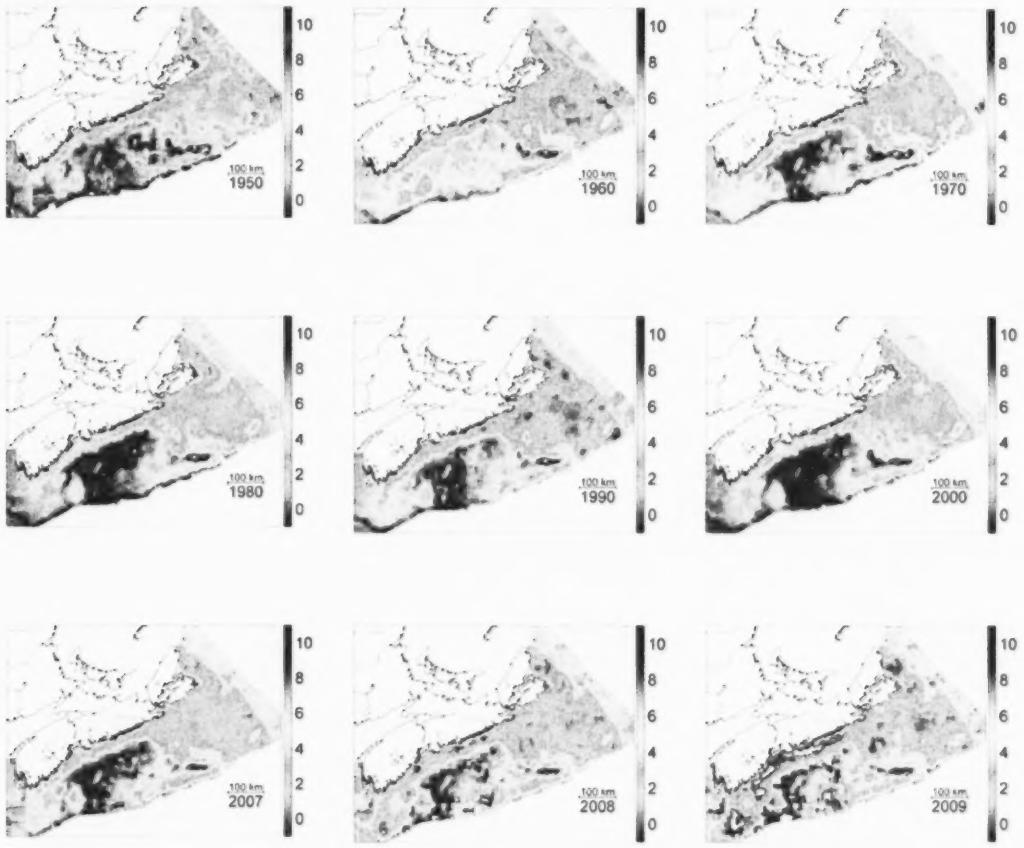


Figure 17. Mean annual bottom temperatures on the Scotian Shelf for selected years.

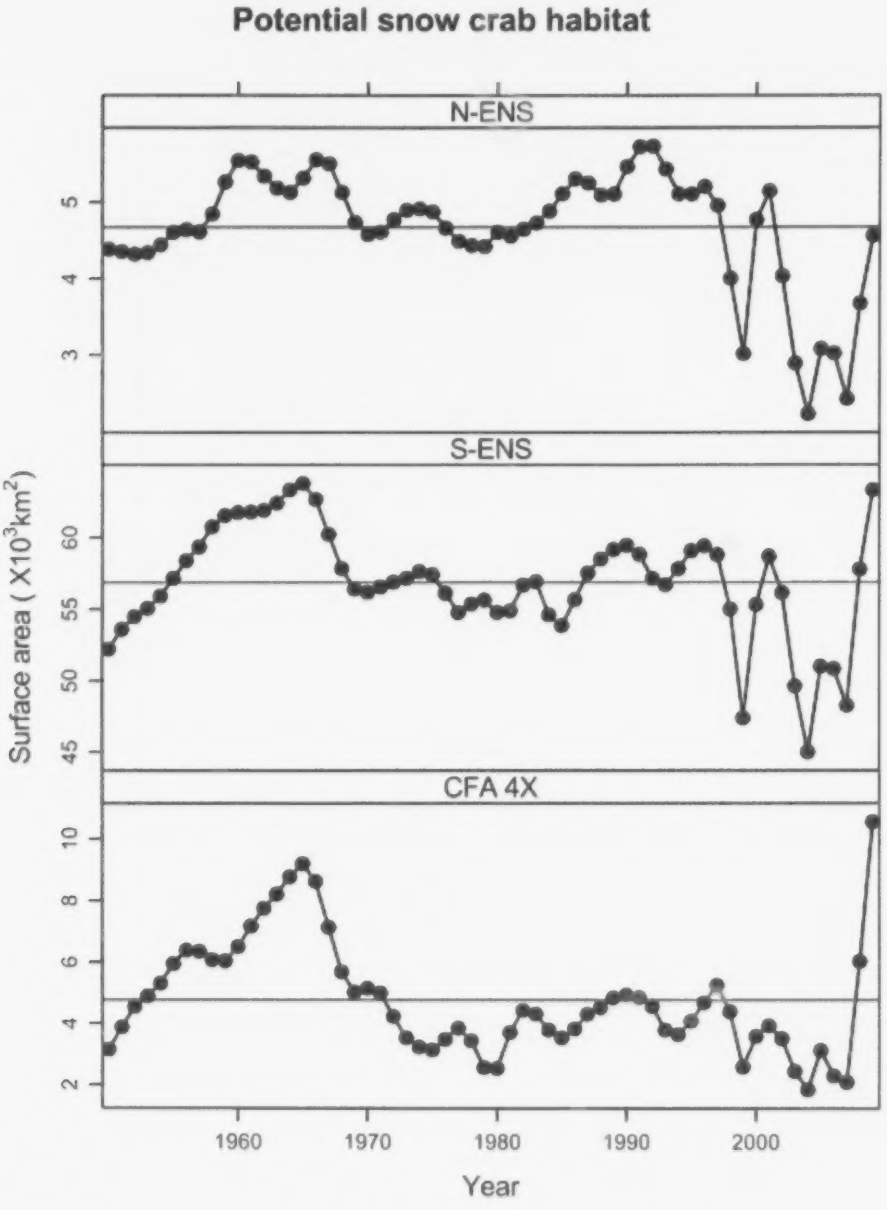


Figure 18. Annual variations in the surface area of potential snow crab habitat. The horizontal line indicates the long-term arithmetic mean surface area within each subarea.

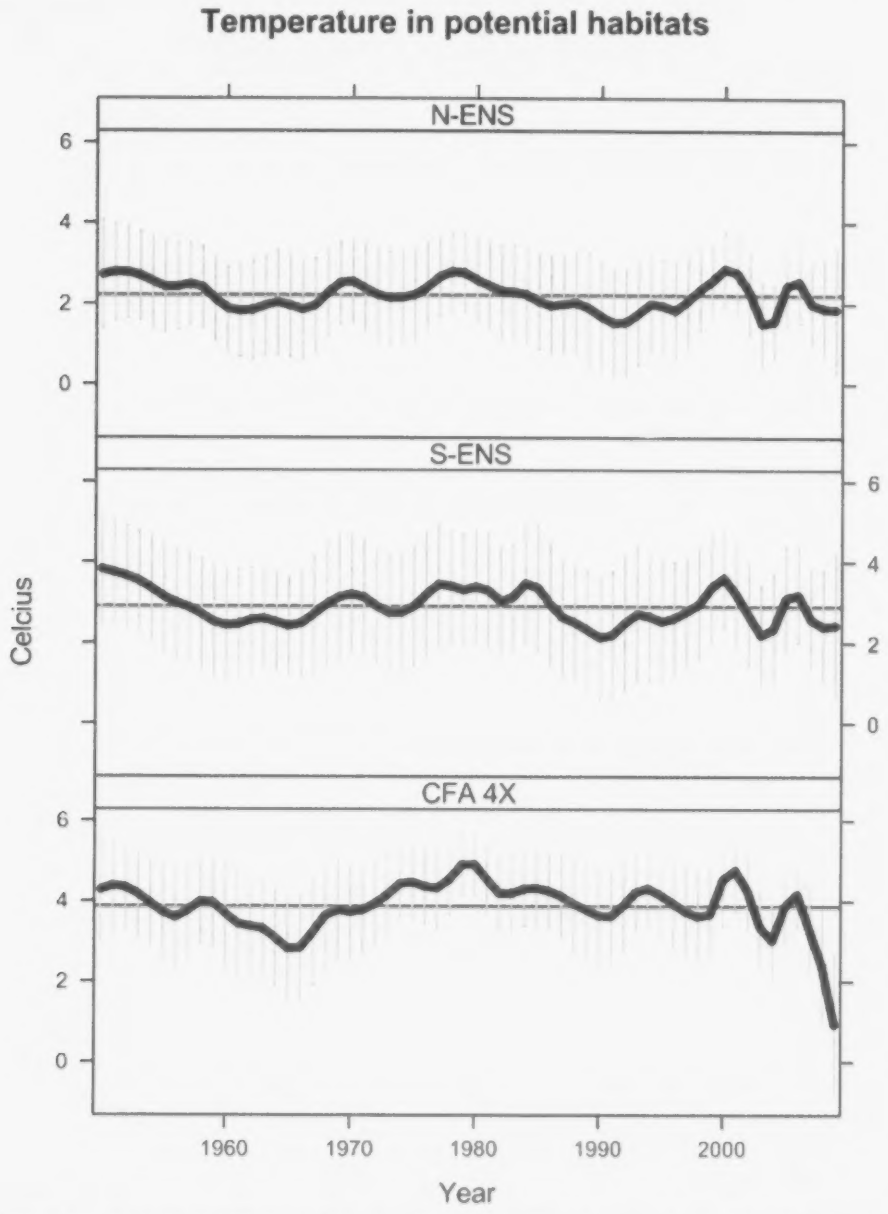


Figure 19. Annual variations in the annual mean bottom temperature within the areas of potential snow crab habitat. The horizontal line indicates the long-term arithmetic mean temperature (1950 to 2009) within each sub-area. Error bars are 1 standard deviation.

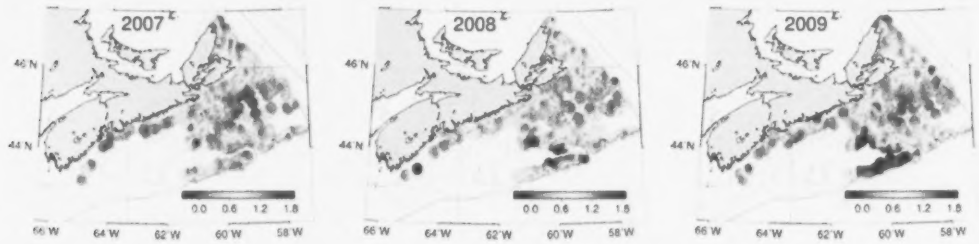


Figure 20. Locations of potential predators of snow crab: cod. Scale is $\log_{10}$ (numerical density [number/km^2]).

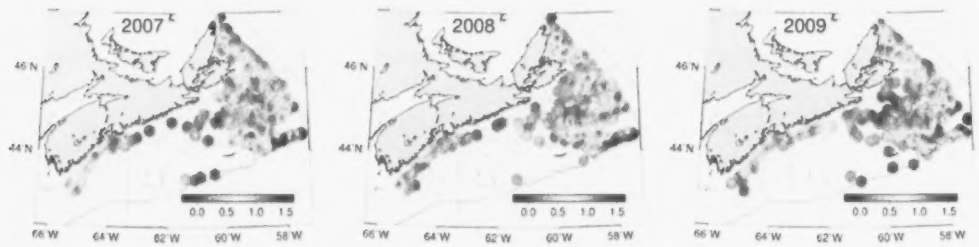


Figure 21. Locations of potential predators of snow crab: thorny skate. Scale is $\log_{10}$ (numerical density [number/km^2]).

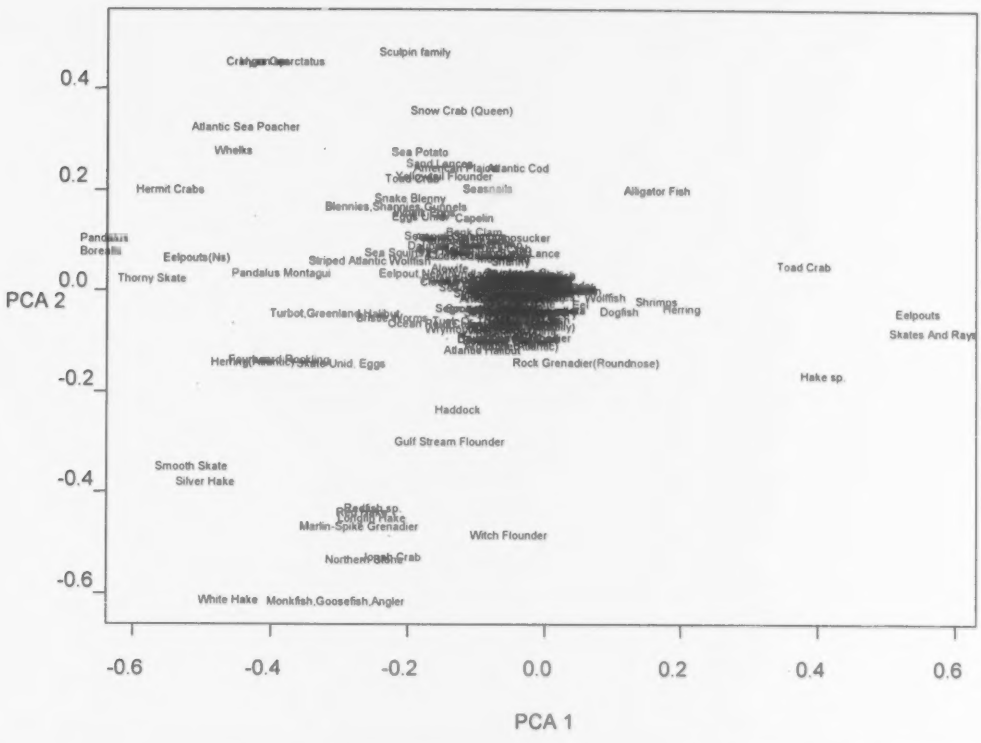


Figure 22. Ordination from a Principle Components Analysis of log-transformed numerical densities based on Pearson correlation matrices.

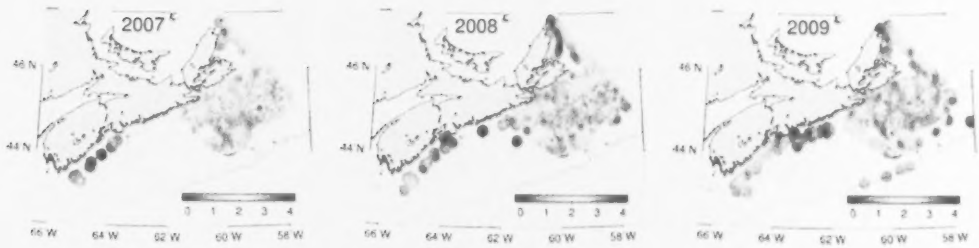


Figure 23. Locations of potential food items of snow crab: northern shrimp. Abundance of these potential food sources roughly match the spatial distributions of snow crab. Scale is $\log_{10}$ (numerical density [number/km^2]).

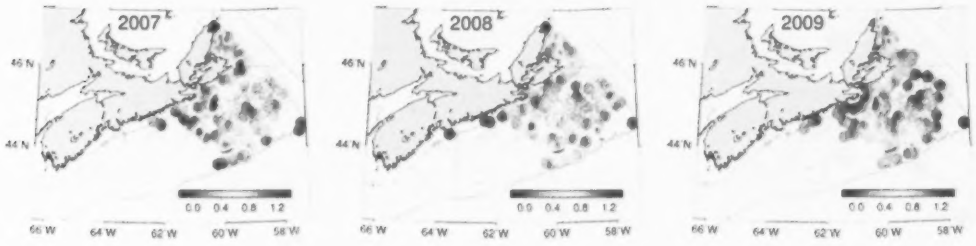


Figure 24. Locations of potential competitors of snow crab: lesser toad crab. High competitive interactions are probable in inshore areas. Scale is $\log_{10}$ (numerical density [number/km^2]).

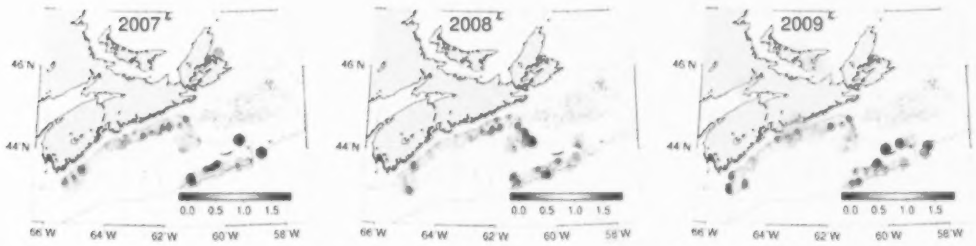


Figure 25. Locations of potential competitors of snow crab: Jonah crab. High competitive interactions are probable in inshore areas. Scale is $\log_{10}$ (numerical density [number/km^2]).

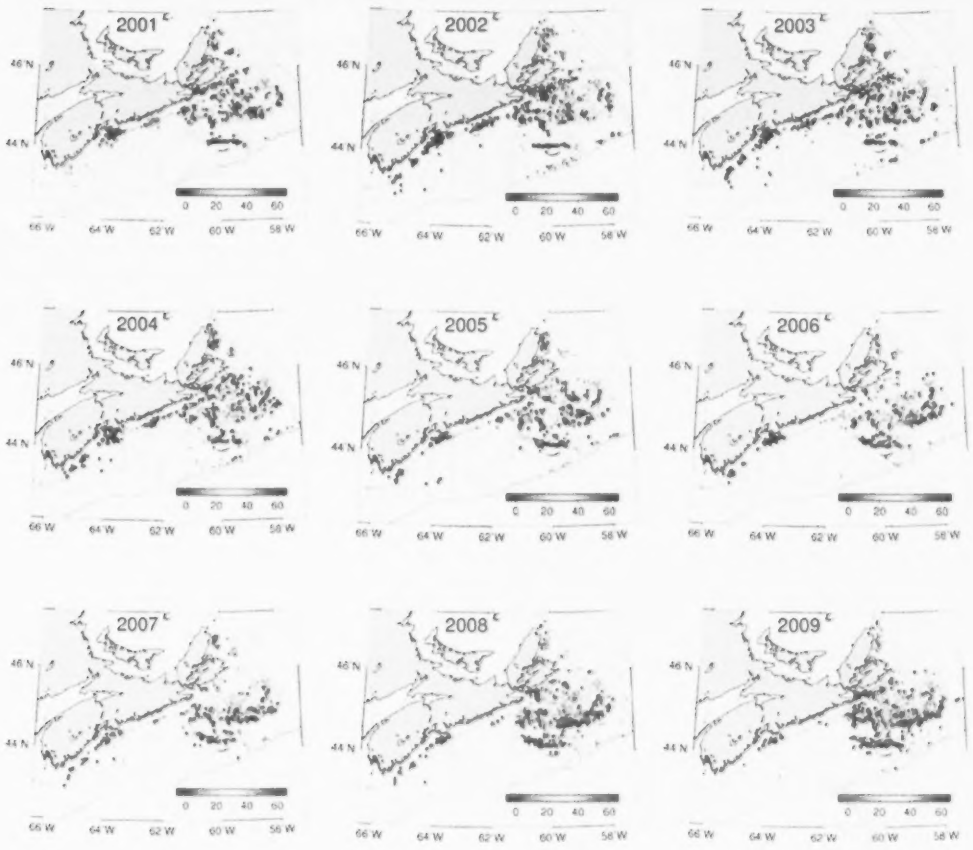


Figure 26. Fishing effort (number of trap hauls / 1 minute grid) from fisheries logbook data. Note the increase in effort offshore and reduction inshore in S-ENS. No visible changes are evident in N-ENS. For CFA 4X, year refers to the starting year.

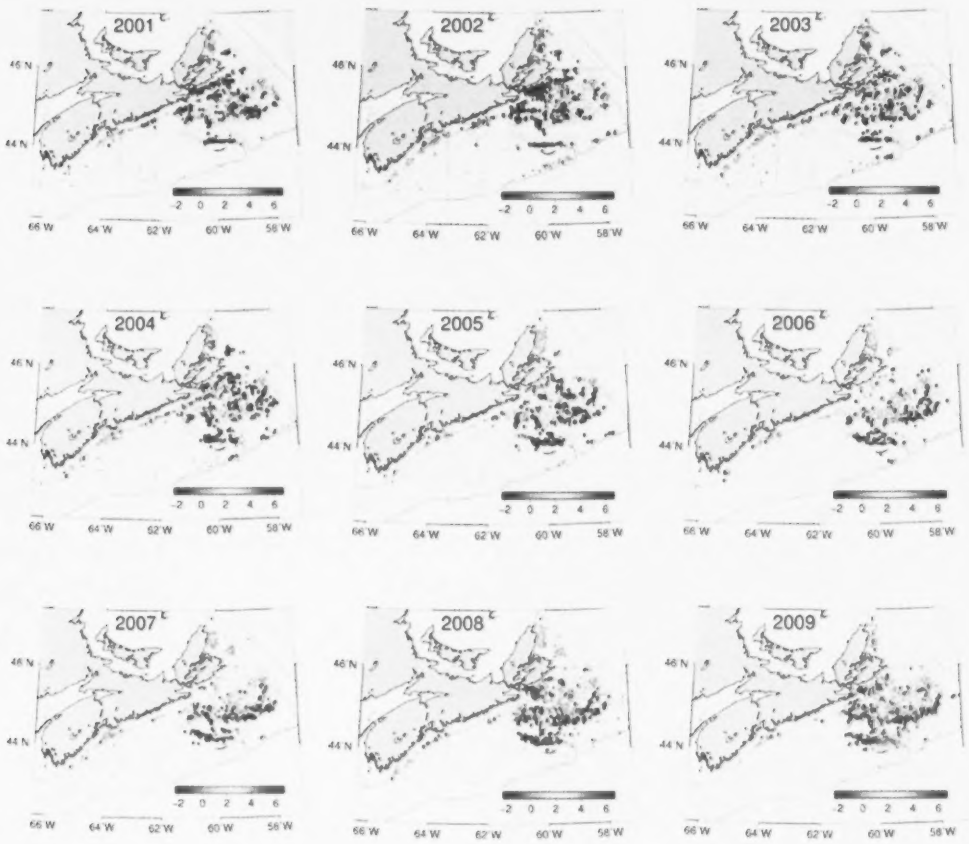


Figure 27. Crab landings (kg / 1 minute grid) from fisheries logbook data. Note the increase in landings offshore and reduction inshore for S-ENS. No visible changes are evident in N-ENS. For CFA 4X, year refers to the starting year.

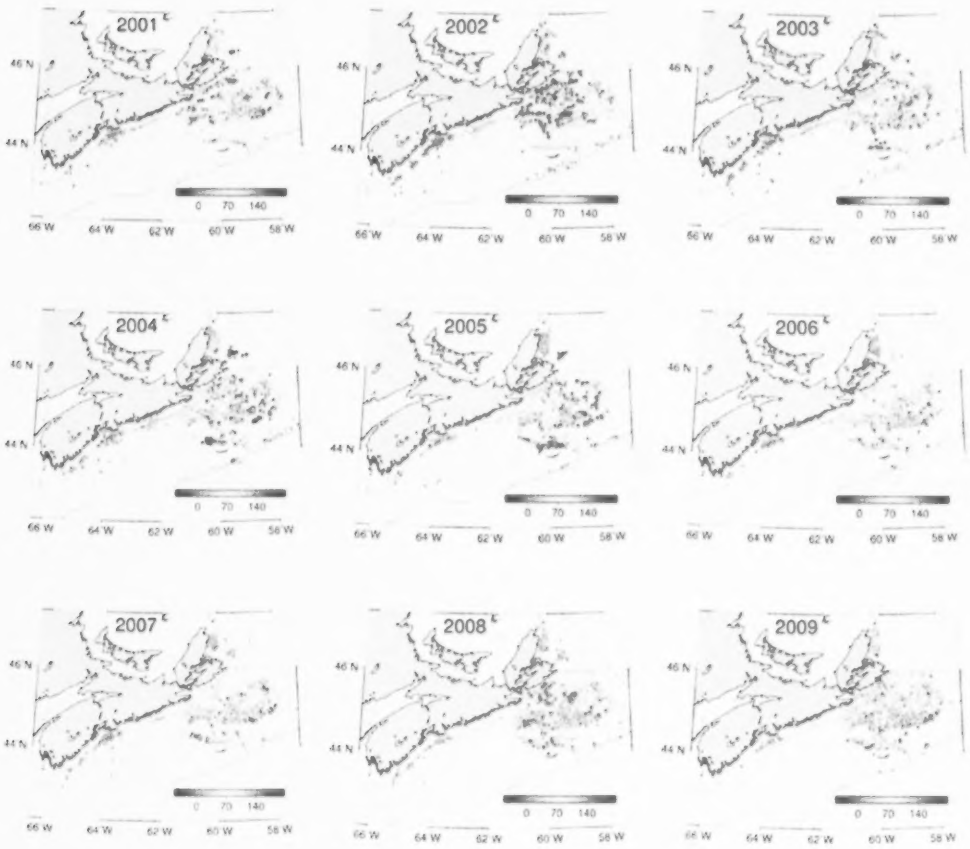


Figure 28. Catch rates (kg trap^{-1}) in each 1 minute grid from logbook data. Note the expansion of fisheries activity to more offshore locations with time. TACs were raised dramatically in 2000. Since that time, large decreases of catch rates in the inshore areas have become evident, indicating strong depletion. The movement to more offshore areas (S-ENS) has offset this lowering of catch rates, where previously unexploited areas became more fully exploited. The temporal increases in crude catch rates of S-ENS are therefore due to the spatial expansion of the targeted areas and the fishers learning to find newer fishing grounds. For CFA 4X, year refers to the starting year.

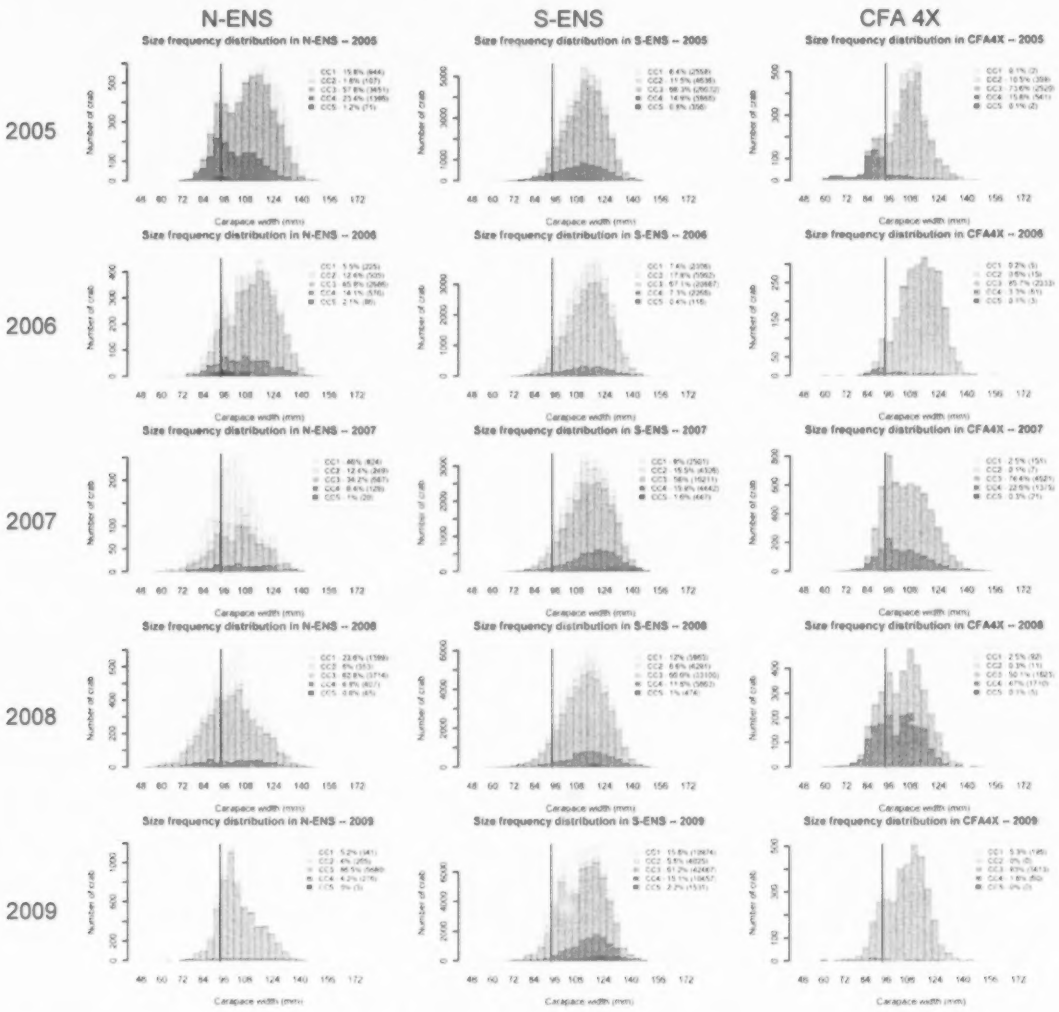

N-ENS
S-ENS
CFA 4X
2005
2006
2007
2008
2009
Size frequency distribution in N-ENS -- 2005
Size frequency distribution in S-ENS -- 2005
Size frequency distribution in CFA4X -- 2005
Size frequency distribution in N-ENS -- 2006
Size frequency distribution in S-ENS -- 2006
Size frequency distribution in CFA4X -- 2006
Size frequency distribution in N-ENS -- 2007
Size frequency distribution in S-ENS -- 2007
Size frequency distribution in CFA4X -- 2007
Size frequency distribution in N-ENS -- 2008
Size frequency distribution in S-ENS -- 2008
Size frequency distribution in CFA4X -- 2008
Size frequency distribution in N-ENS -- 2009
Size frequency distribution in S-ENS -- 2009
Size frequency distribution in CFA4X -- 2009
Number of crab
Carapace width (mm)

Figure 29. Size frequency distribution of all at-sea-observer monitored snow crab broken down by carapace condition. For CFA 4X, the year refers to the starting year of the season. Vertical lines indicate 95 mm CW.

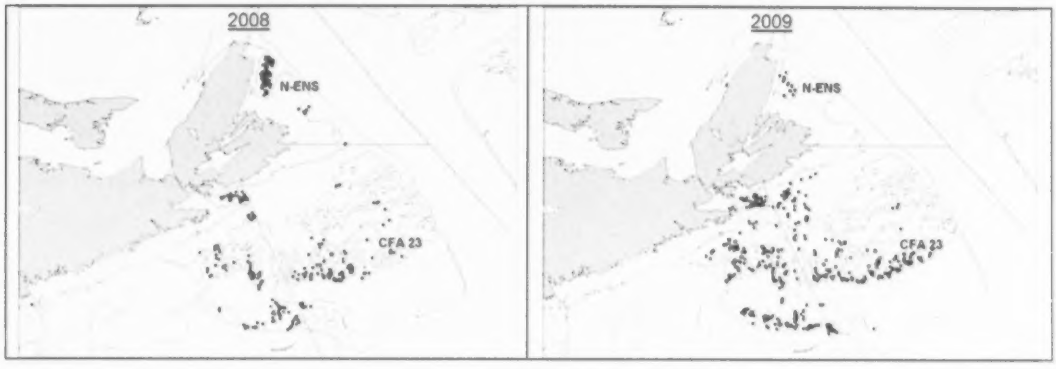


Figure 30. Location of ≥20% soft-shell snow crab occurrence in ENS.

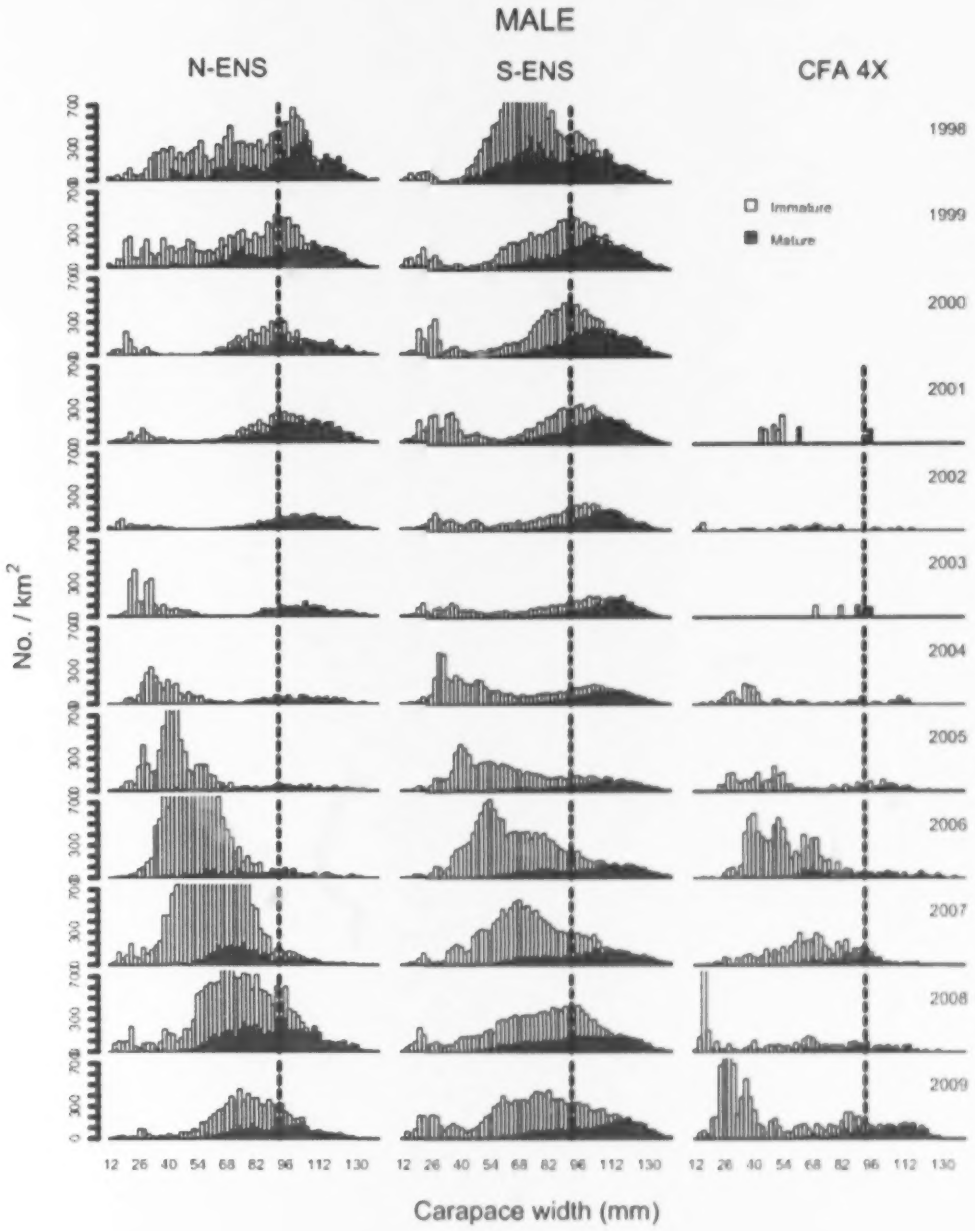


Figure 31. Size-frequency histograms of carapace width of male snow crabs. Note the increasing numbers of juvenile crab, 1 to 3 years from entering morphometrically mature size classes. Due to the expansion of the survey from core areas to the full extent of the snow crab grounds, the areal densities of crab in S-ENS and CFA 4X are not directly comparable between all years. For N-ENS, however, the relative heights are comparable. For S-ENS and CFA 4X, 2004 to the present are comparable.

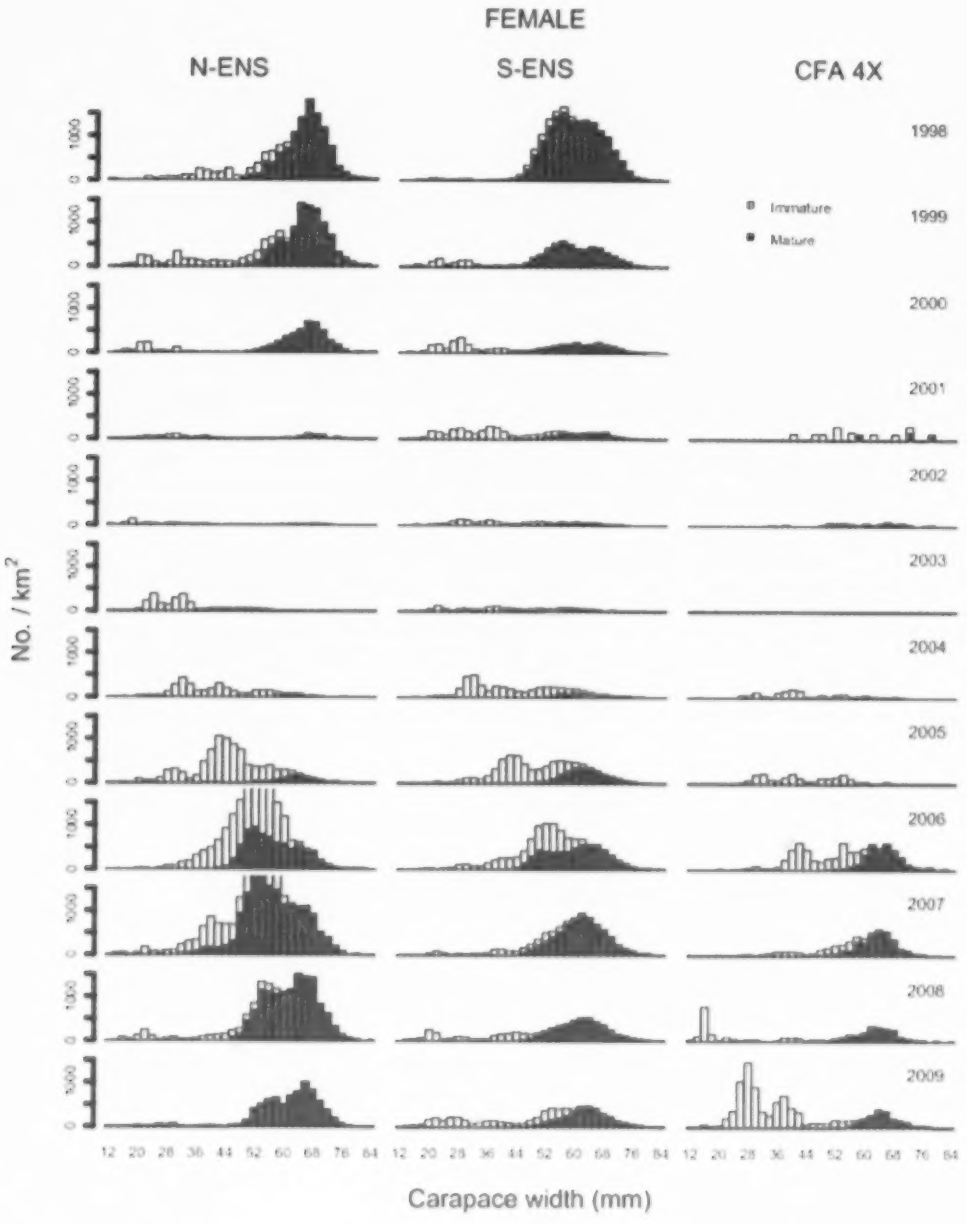


Figure 32. Size-frequency histograms of carapace width of female snow crabs. Note the increasing numbers of juvenile crab in recent years. The leading edge of the recruitment pulse has begun to enter morphometrically mature size classes. Due to the expansion of the survey from core areas to the full extent of the snow crab grounds, the areal densities of crab in S-ENS and CFA 4X are not directly comparable between all years. For N-ENS, the relative heights are comparable between all years. For S-ENS and CFA 4X, data from 2004 to the present are comparable.

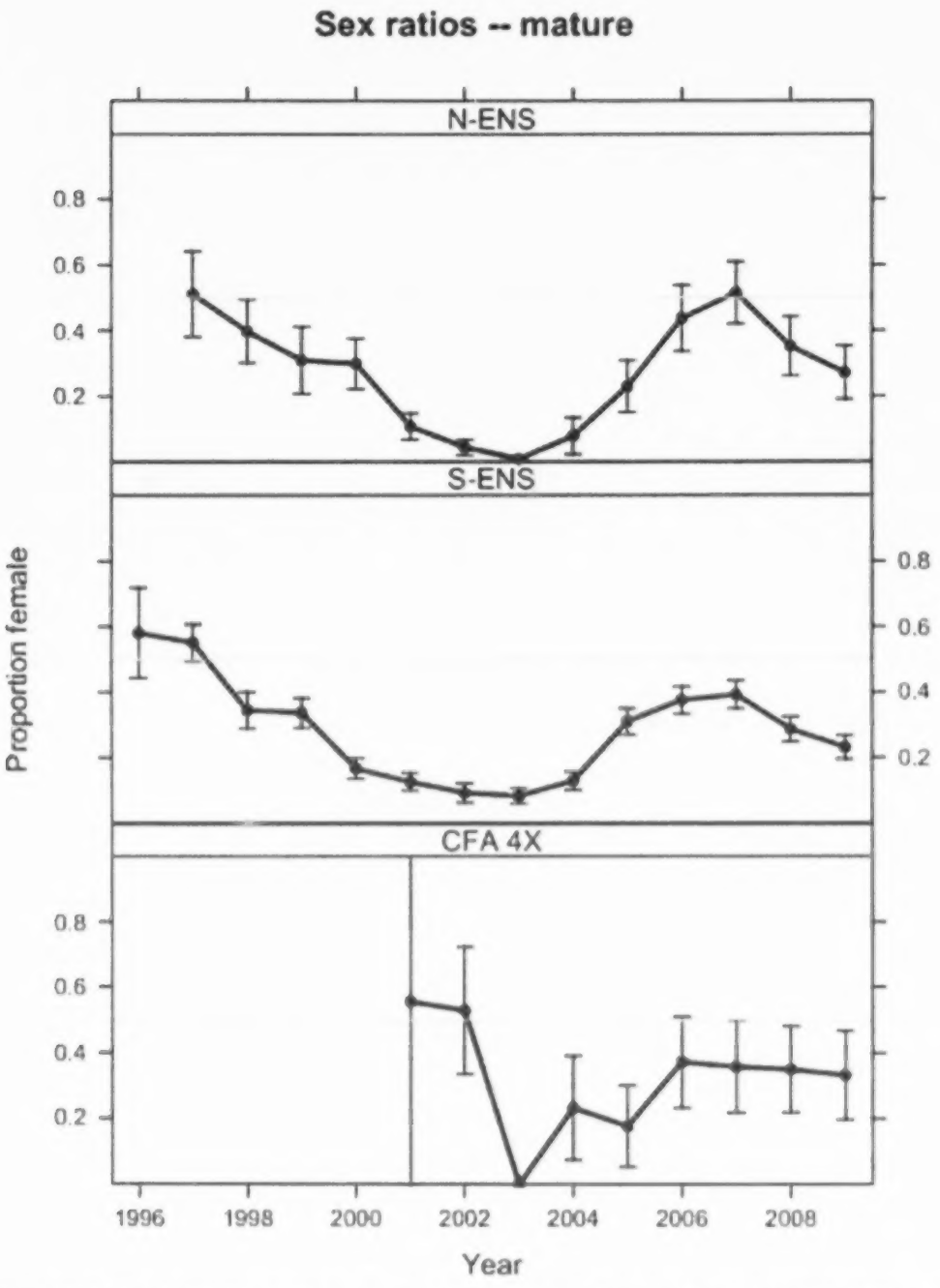


Figure 33. Annual variations in the mean sex ratio (proportion female) for morphometrically mature crabs. One standard error bars are presented.

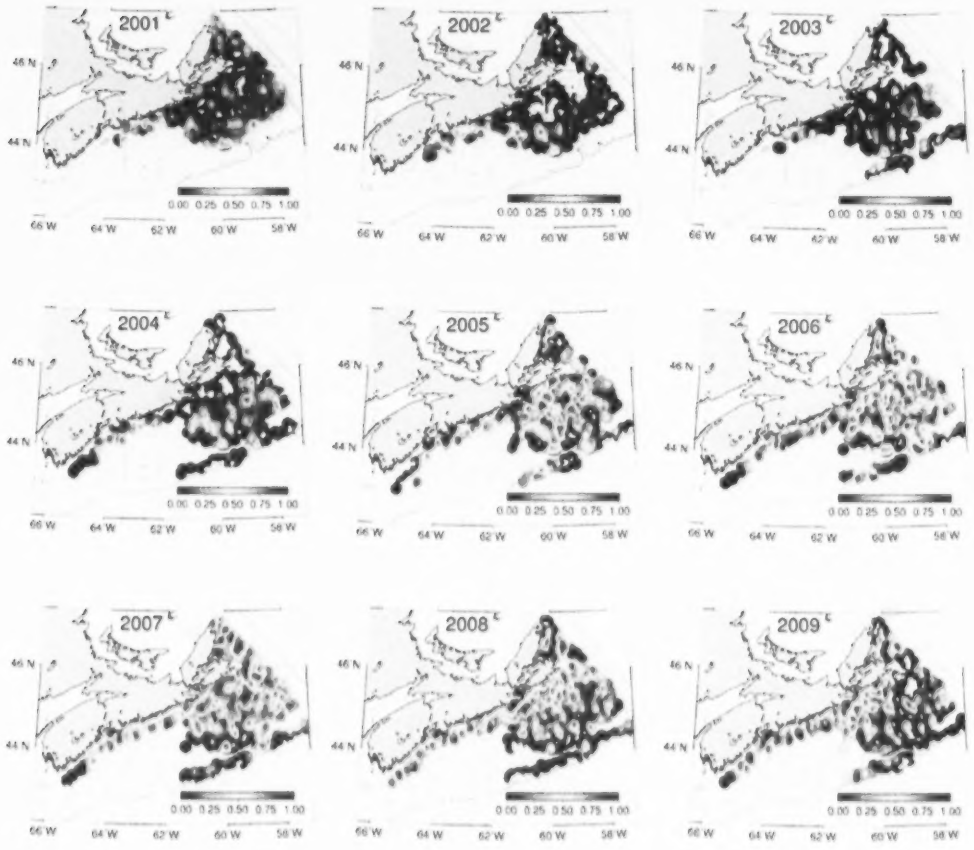


Figure 34. Morphometrically mature sex ratios (proportion female).

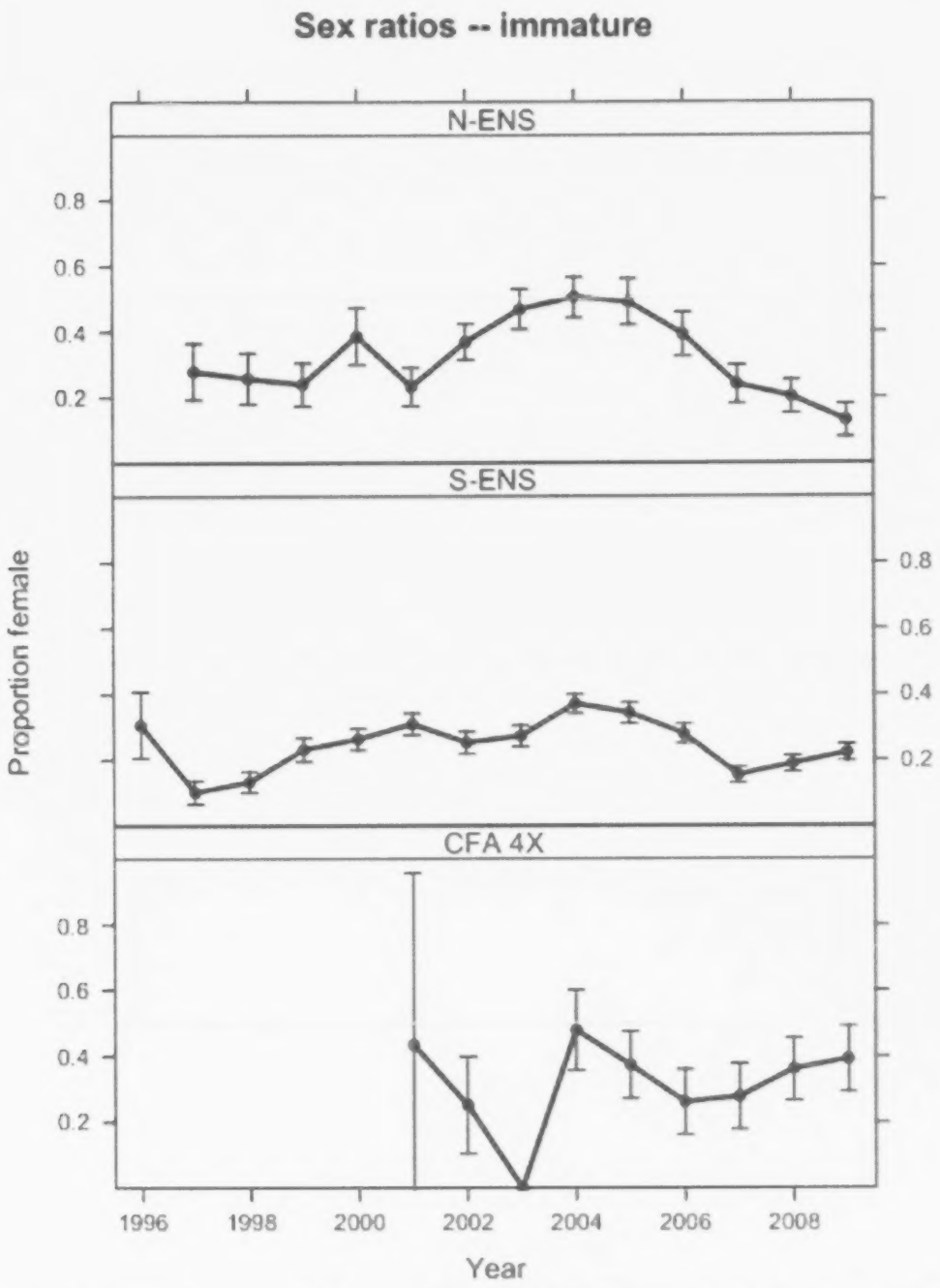


Figure 35. Annual variations in the mean sex ratio (proportion female) for morphometrically immature crabs. One standard error bars are presented.

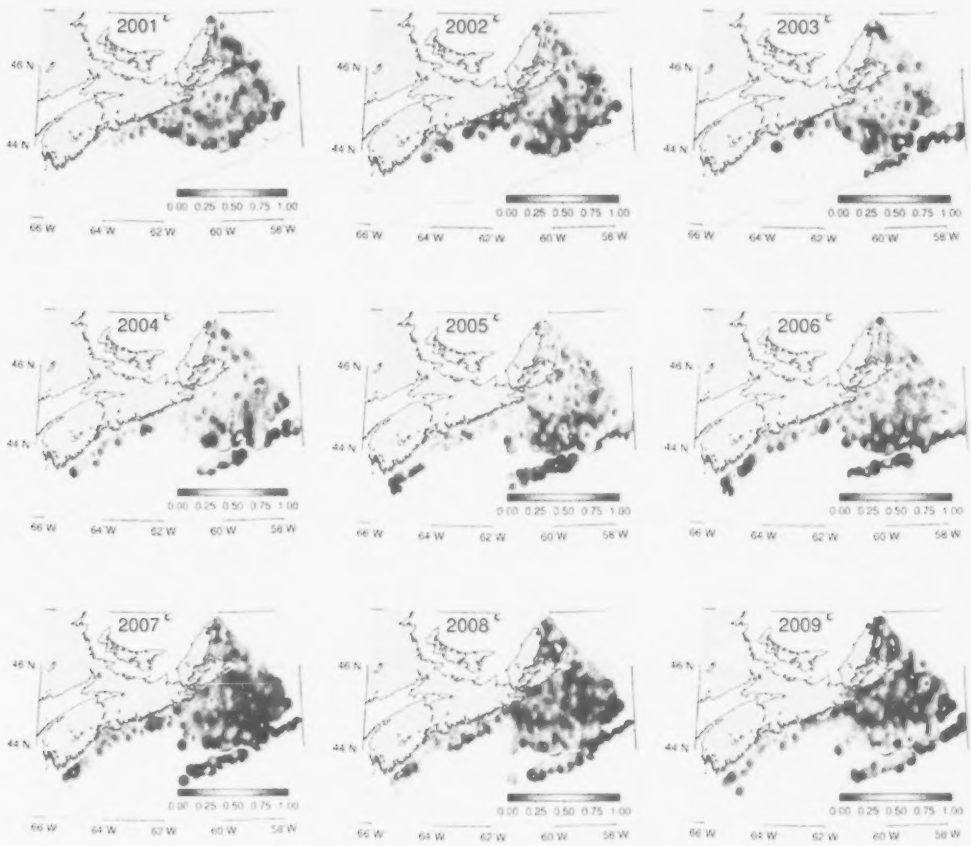


Figure 36. Morphometrically immature sex ratios (proportion female).

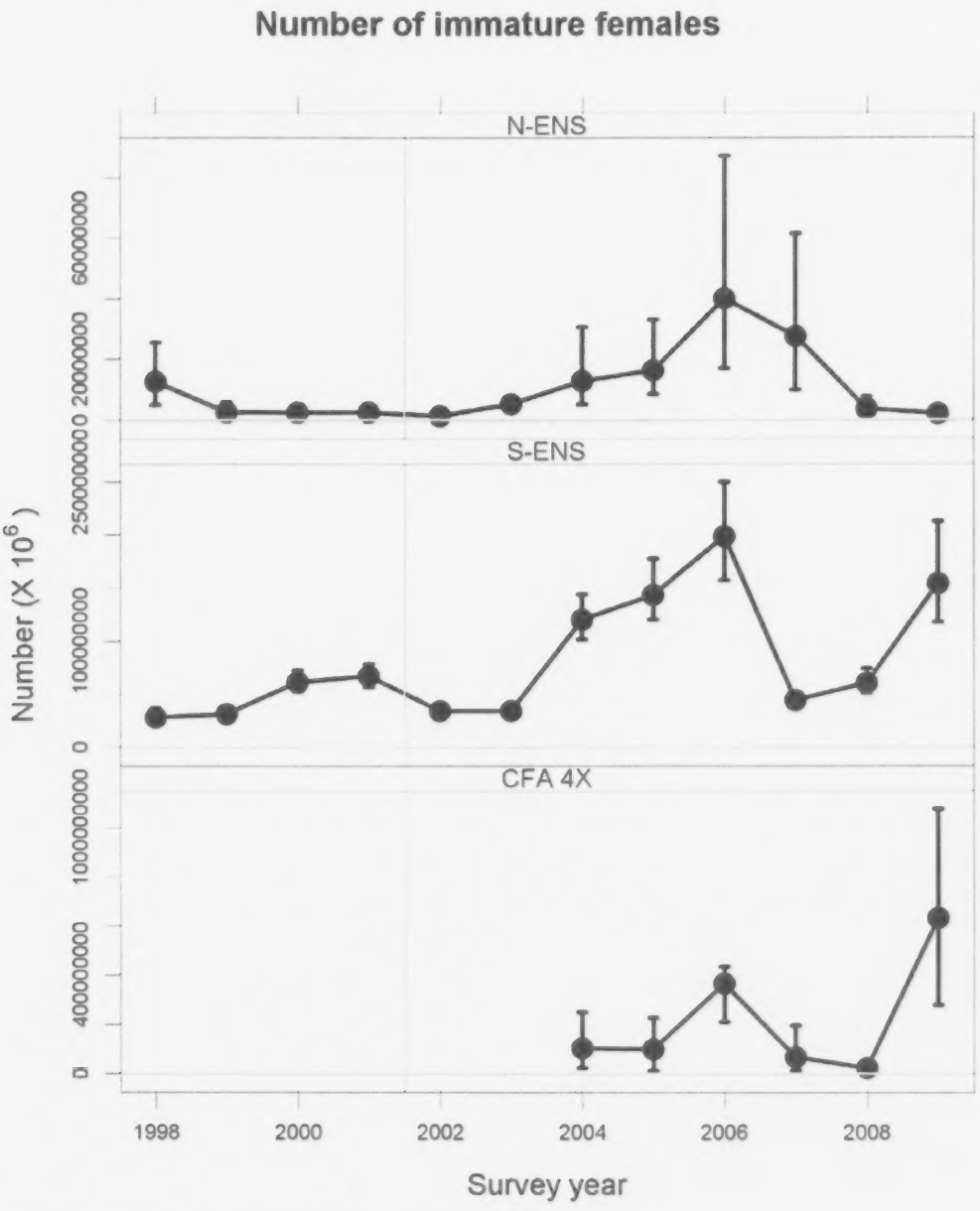


Figure 37. Number of immature females in the SSE.

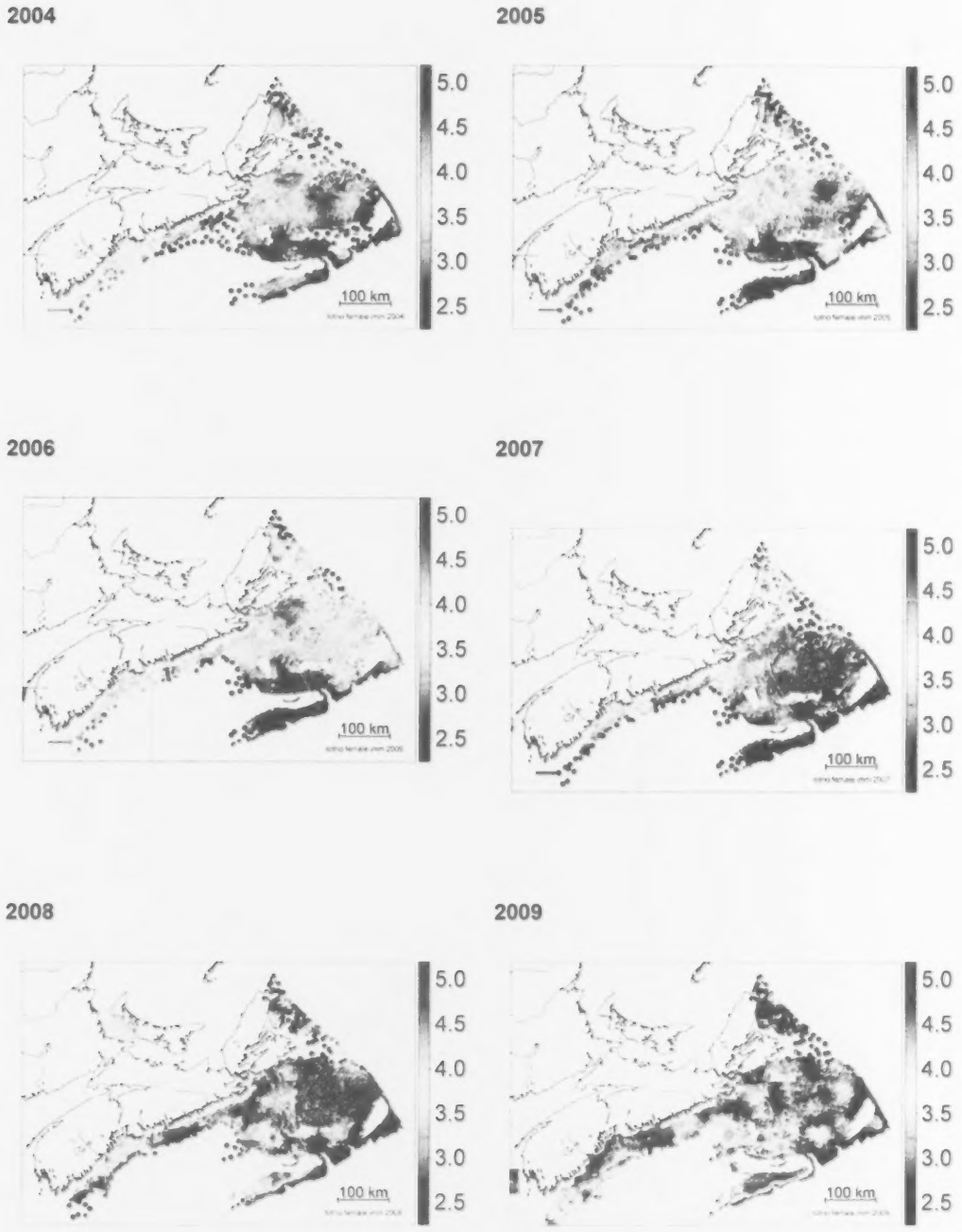


Figure 38. Numerical densities of the immature female snow crabs on the Scotian Shelf; $\log_{10}(\text{number/km}^2)$.

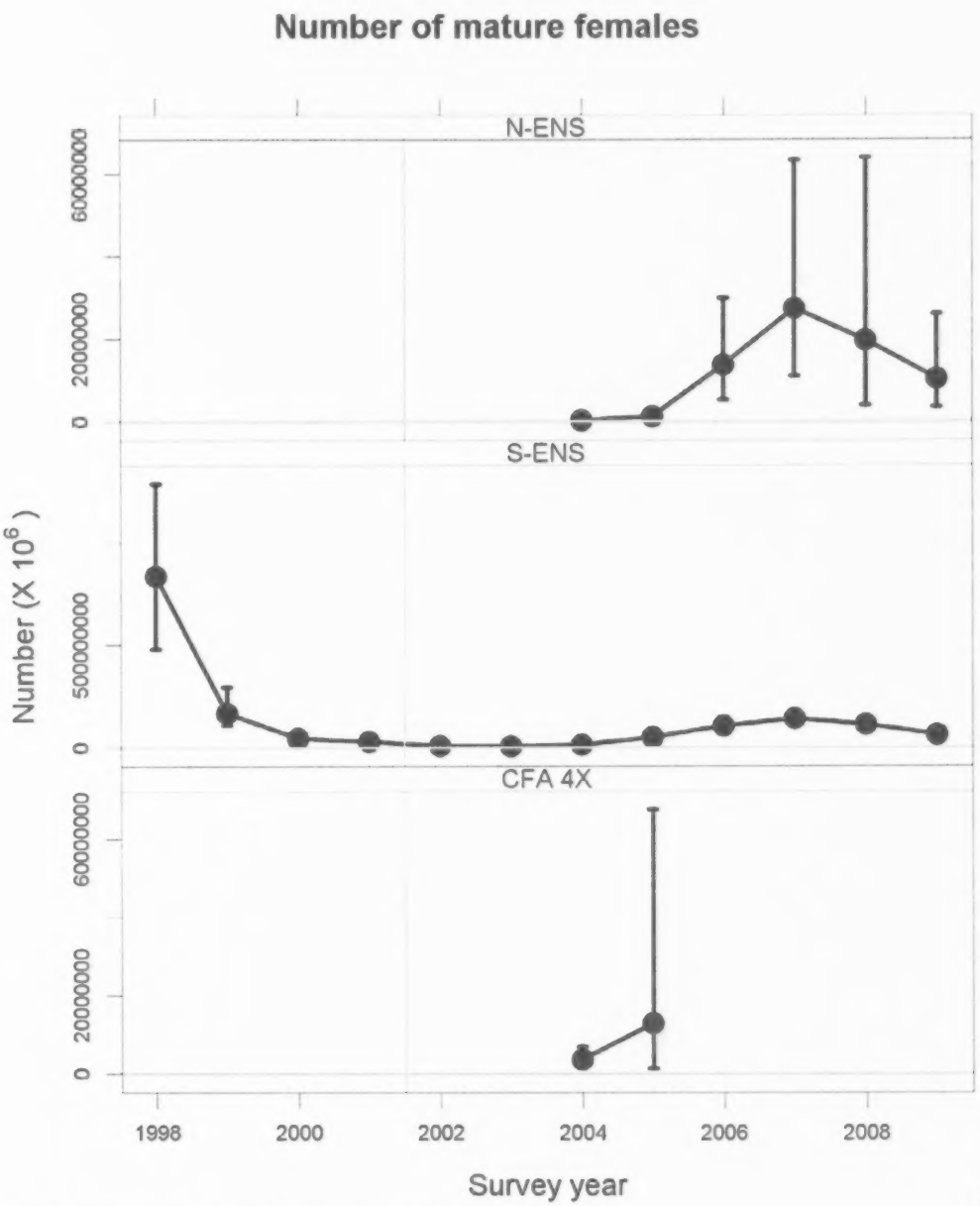
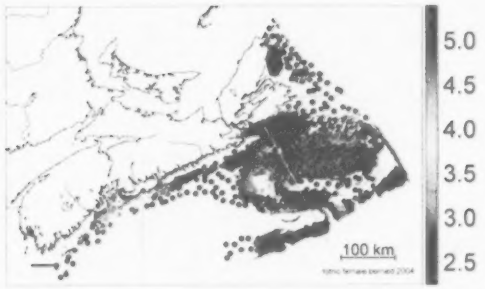
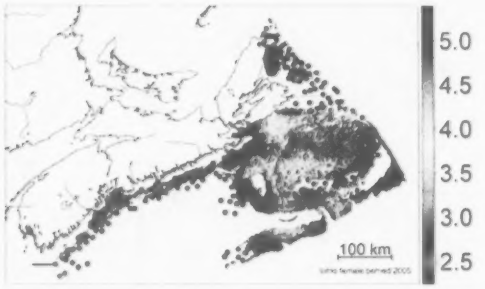


Figure 39. Number of mature females in the SSE.

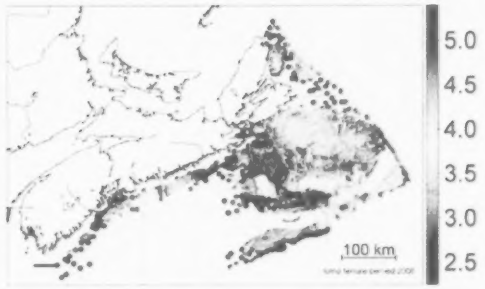
2004



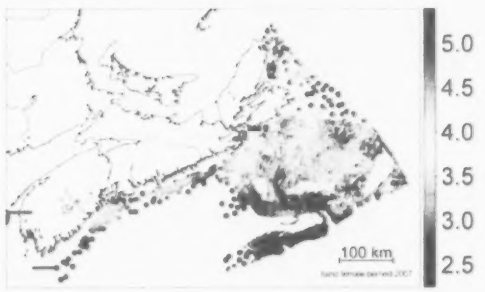
2005



2006



2007



2008

2009

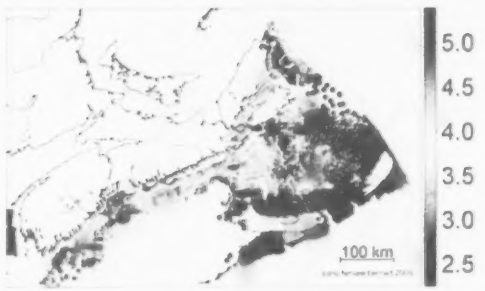


Figure 40. Numerical densities of the berried female snow crabs on the Scotian Shelf; $\log_{10}$ (number/km^2).

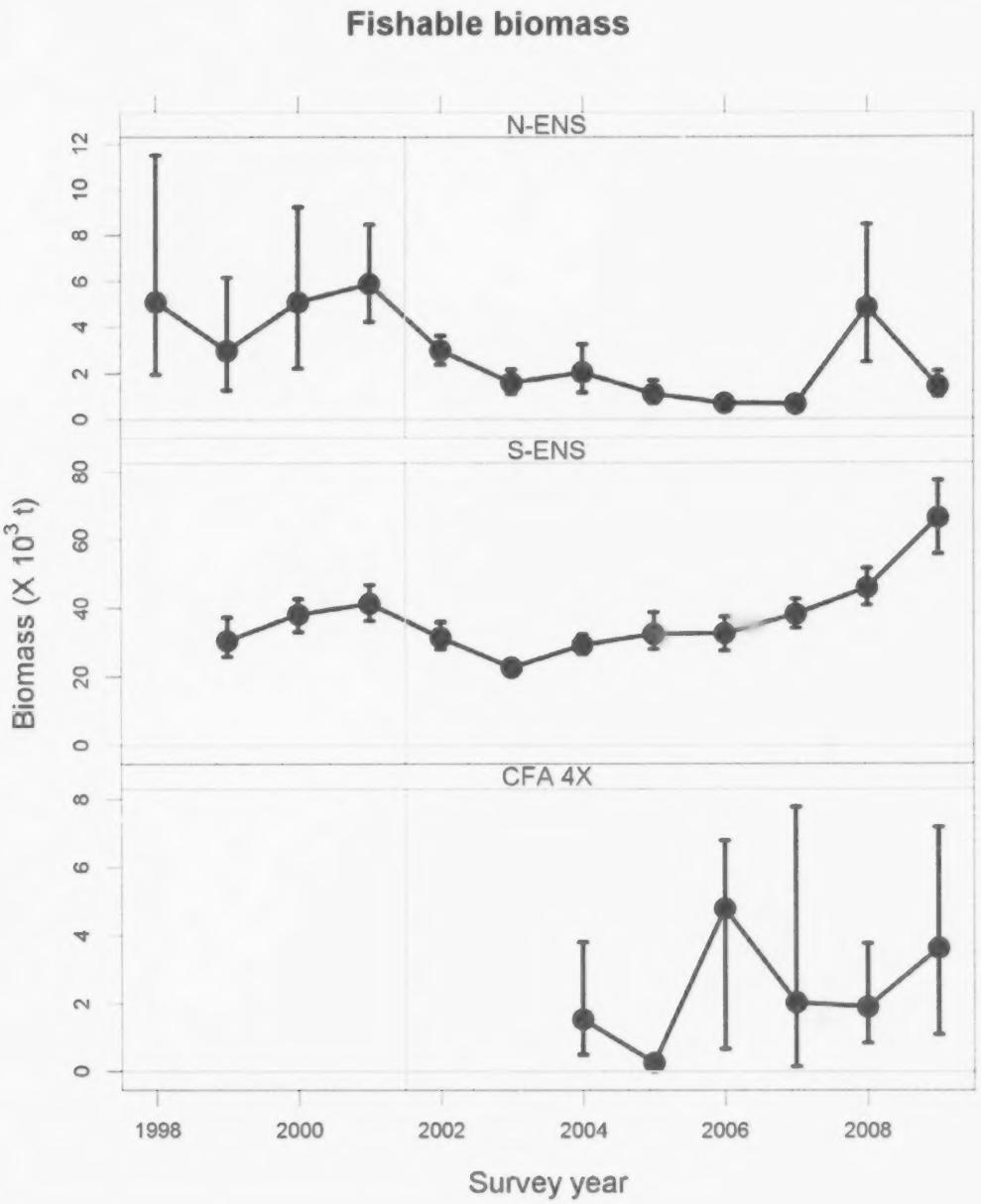


Figure 41. Temporal variations in fishable biomass estimates. Error bars are 95% confidence intervals about the estimated total biomass. The vertical line near 2002 indicates the period in which trawl surveys changed from a spring to an autumn sampling period.

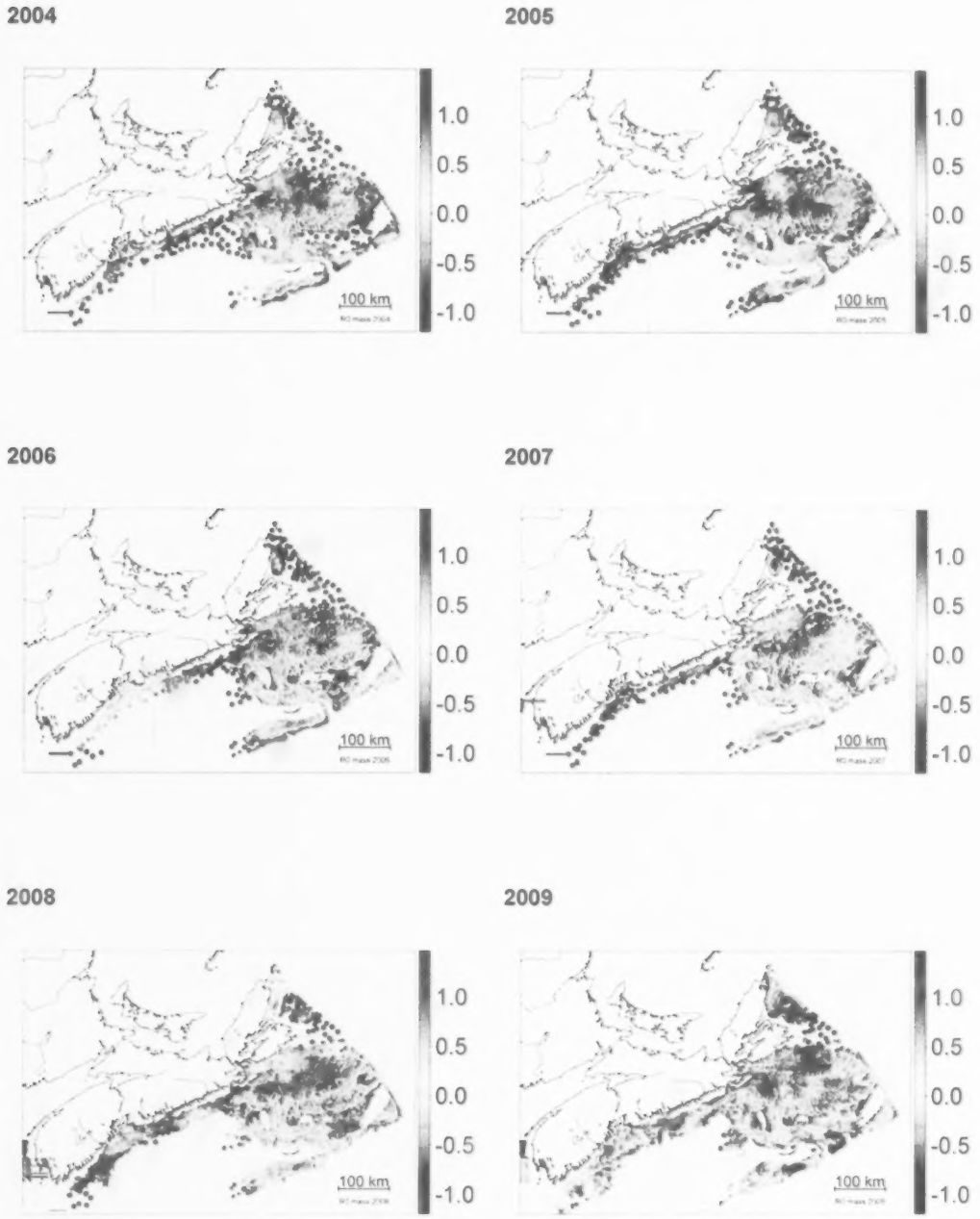


Figure 42. Fishable biomass densities on the Scotian Shelf; $\log_{10}$ (t/km^2).

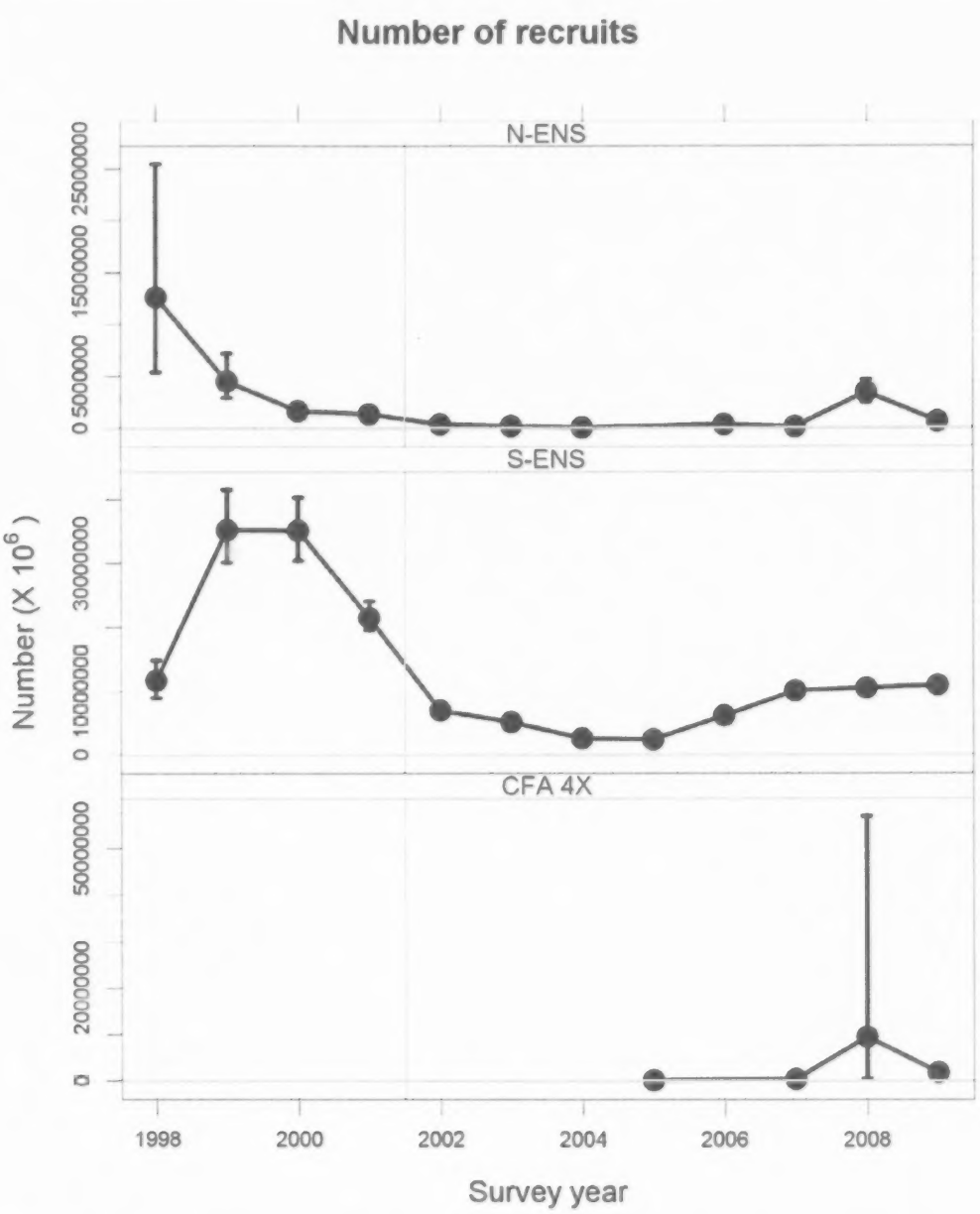


Figure 43. Recruitment into the fishable biomass. As surveys are conducted in the autumn (since 2002/2003), the majority of recruitment into the fishable biomass has already occurred. This figure shows the additional recruitment expected that has not yet become part of the fishable biomass. Error bars are 95% confidence intervals about the estimated total biomass. The vertical line near 2002 indicates the period in which trawl surveys changed from a spring to an autumn sampling period.

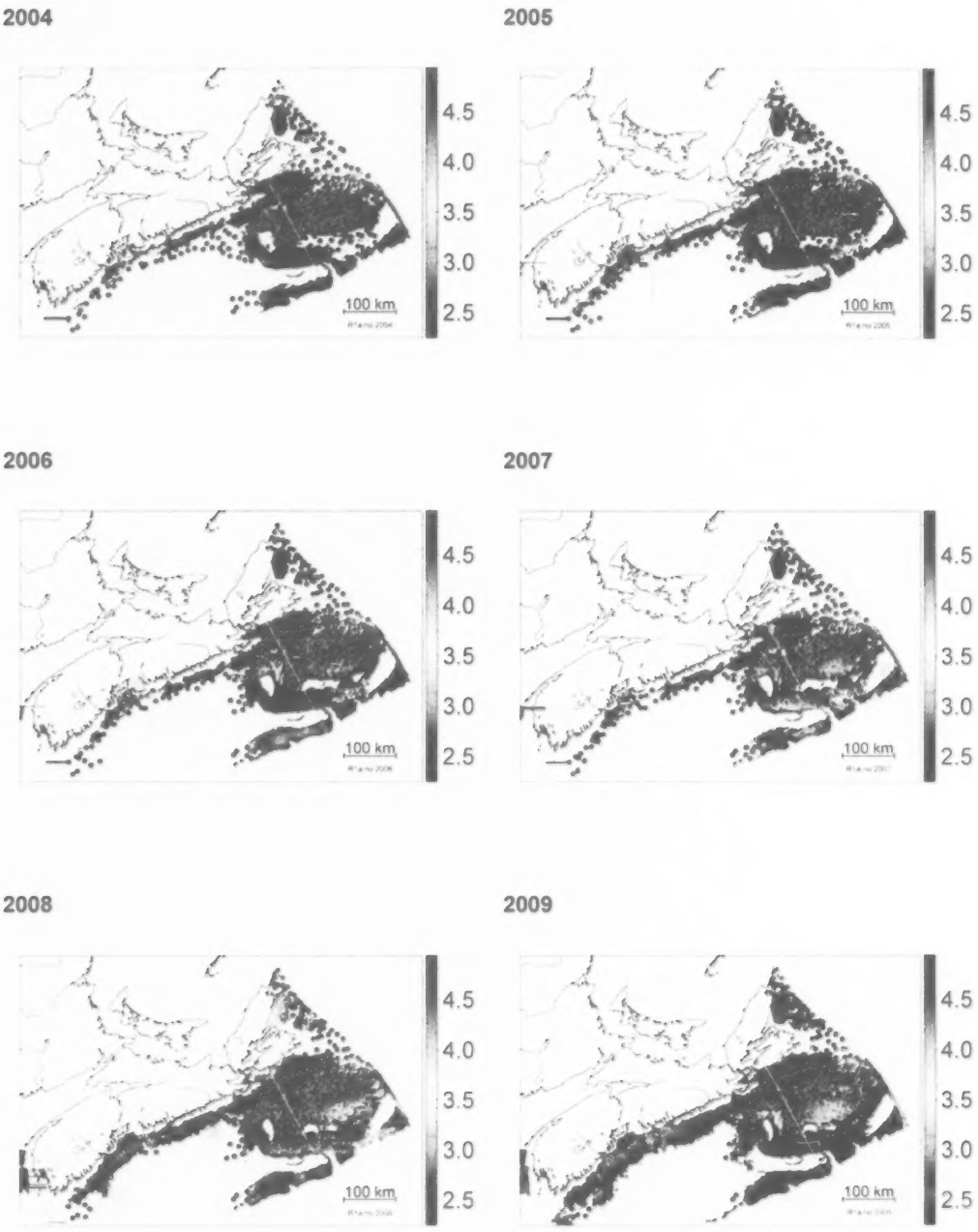


Figure 44. Numerical densities of snow crab recruiting into the next year; $\log_{10}$ (number/km^2).

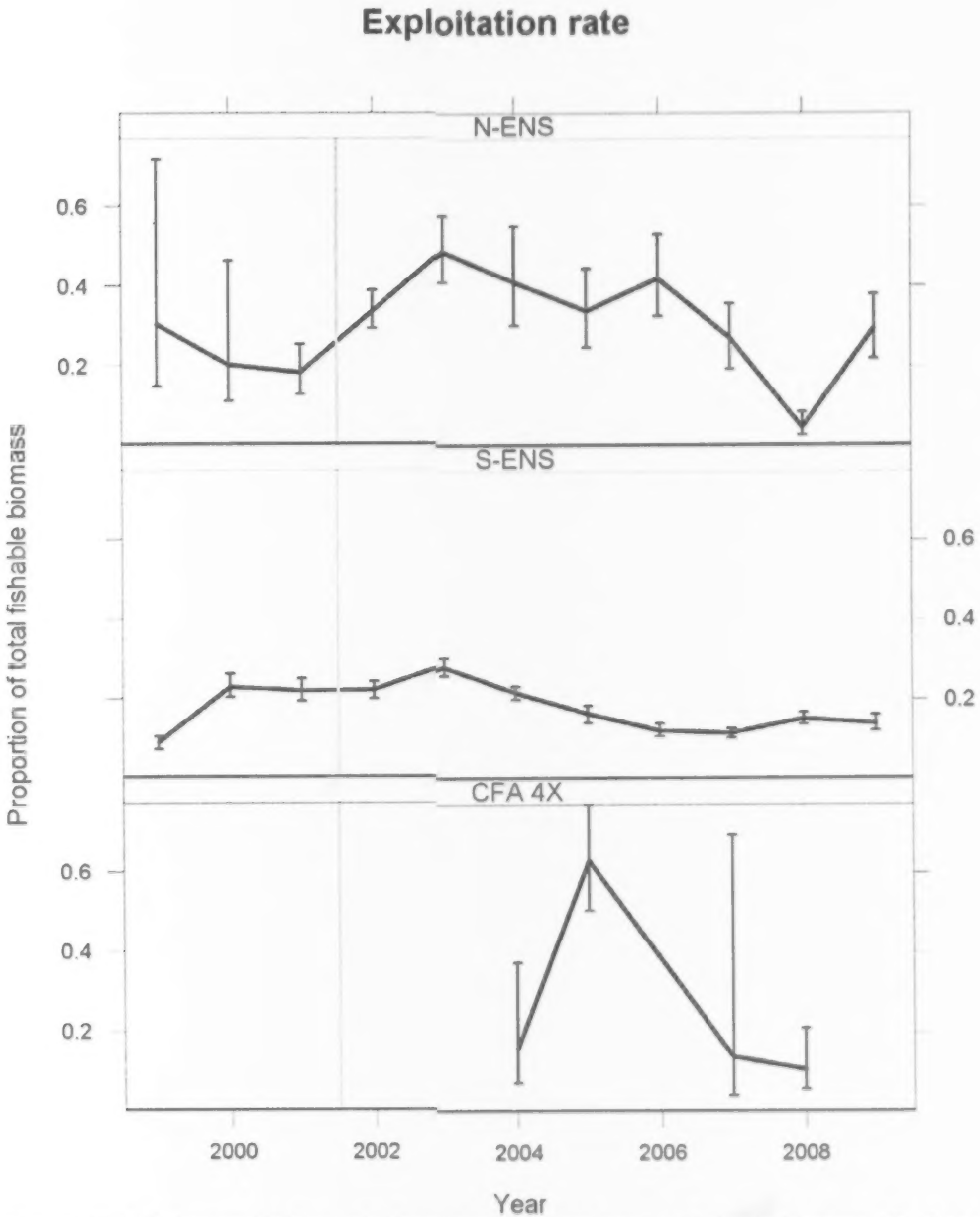


Figure 45. Relative exploitaiton rate (Landings$_{(t)}$ / [Landings$_{(t)}$ + Fishable biomass$_{(t)}$]) of snow crab. Vertical line represents the shift in survey timing from spring to autumn.

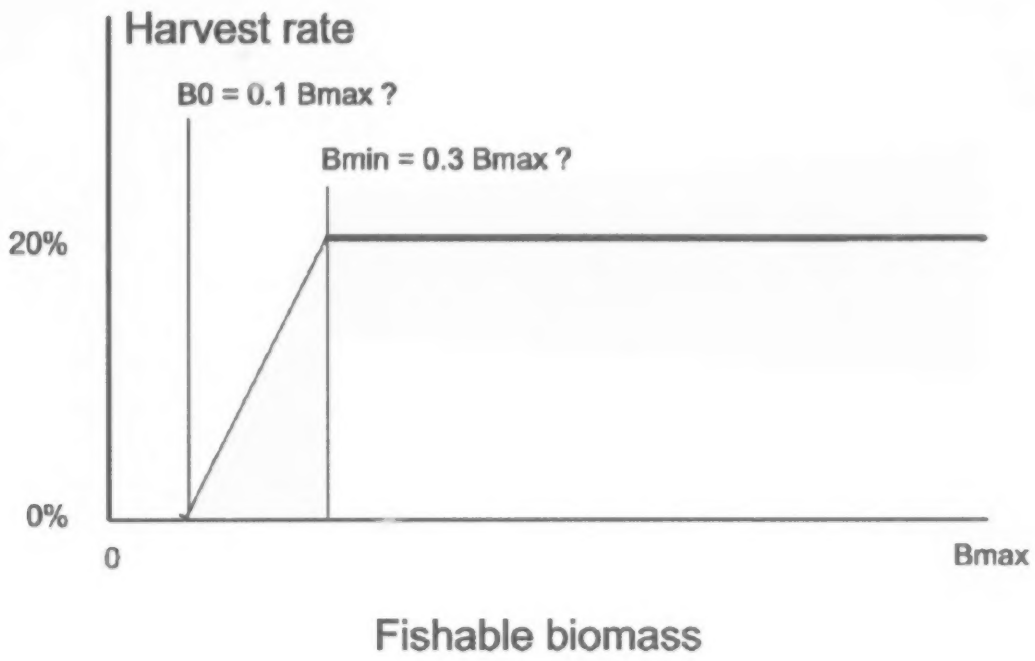


Figure 46. Proposed harvest control rules.

Appendix 1. Ecosystem indicators.

The variables used as indicators in this study are listed and described in the following:

NS: Population size	Total population size for Nova Scotia, a proxy of the influence of human of the Scotian Shelf
CIL volume	Cold intermediate layer (water temperature < 3 C) in the Gulf of St. Lawrence from the September groundfish hydrographic survey.
CPR: Calanus finmarchicus 1-4	Continuous Plankton Recorder (CPR) relative abundance estimates: Calanus finmarchicus instars 1 to 4
CPR: Calanus finmarchicus 5-6	Continuous Plankton Recorder (CPR) relative abundance estimates: Calanus finmarchicus instars 5 to 6
CPR: colour	Continuous Plankton Recorder (CPR) relative estimate surface ocean colour, a proxy for Chl-a concentrations
CPR: diatoms	Continuous Plankton Recorder (CPR) relative abundance estimates: Diatoms
CPR: dinoflagellates	Continuous Plankton Recorder (CPR) relative abundance estimates: Dinoflagellates
Employment per total landed value	Number of fishers employed per total landed value of the fishery
Employment per total landings	Number of fishers employed per total landings of fish
GDP: fish processing	Gross Domestic Product: fish processing sector in Nova Scotia
GDP: fishing and hunting	Gross Domestic Product: fishing and hunting sector in Nova Scotia
GDP: NS total	Gross Domestic Product:Total for Nova Scotia
GDP: oil and gas	Gross Domestic Product: Oil and gas sector in Nova Scotia
Gulf stream front: lat@-62 lon	Gulf stream front location at -62 longitude (latitude)
Ice coverage	Sea ice coverage, cumulative seasonal sum
Landed value: all	Landed value of all fish and invertebrates
Landed value: groundfish	Landed value of all groundfish in Nova Scotia
Landed value: pelagics	Landed value of all pelagic fish in Nova Scotia
Landed value: shellfish	Landed value of all shellfish
Landings: all	Total landings of all fish and invertebrates
Landings: groundfish	Total landings of all groundfish
Landings: pelagic	Total landings of all pelagic fish
Landings: shellfish	Total landings of all shellfish
NAO index	North Atlantic Oscillation index anomaly of December-February sea level atmospheric pressure difference (kPa) between the Azores and Iceland. This index has been shown to be related to air temperatures, SST, convection and circulation changes in the North Atlantic and through atmospheric teleconnections, even broader-scale forcings.
No. fish harvesters	Number of fish harvesters in Nova Scotia
No. shellfish closures	Number of shellfish closures
No. wells drilled	Number of oil and gas wells drilled on the Scotian Shelf
NS: % 65 and older	Nova Scotia demographics
NS: % attending university	Nova Scotia demographics
PCBs: puffins	PCB concentrations in Atlantic puffins
PCBs: seals	PCB concentrations in Grey seals
RV: biomass capelin	Research survey estimates of capelin biomass

RV: biomass cod	Research survey estimates of cod
RV: biomass elasmobranchs	Research survey estimates of elasmobranch fish
RV: biomass flatfish	Research survey estimates flatfish
RV: biomass gadoids	Research survey estimates gadoids
RV: biomass large demersals	Research survey estimates large demersal fish
RV: biomass large pelagics	Research survey estimates large pelagic fish
RV: biomass small demersals	Research survey estimates of small demersal fish
RV: biomass small pelagics	Research survey estimates small pelagic fish
RV: bottom oxygen	Research survey estimates of bottom oxygen concentration
RV: bottom salinity	Research survey estimates bottom salinity
RV: bottom temperature	Research survey estimates bottom temperature
RV: condition elasmobranchs	Research survey estimates of elasmobranch physiological condition
RV: condition flatfish	Research survey estimates of flatfish physiological condition
RV: condition gadoids	Research survey estimates of gadoid physiological condition
RV: condition large demersals	Research survey estimates of large demersal physiological condition
RV: condition large pelagics	Research survey estimates of large pelagic physiological condition
RV: condition small demersals	Research survey estimates of small demersal physiological condition
RV: condition small pelagics	Research survey estimates of small pelagics physiological condition
RV: groundfish SMR	Research survey estimates of mass specific metabolic rates of all fish
RV: no. taxa predicted at 100 km2	Research survey estimates of the number of taxa predicted at 100 km^2
RV: Shannon index	Research survey estimates of the Shannon diversity index of fish species
RV: species-area exponent	Research survey estimates the mean species-area exponent on the Scotian Shelf. The average scaling exponent derived from a species richness vs surface area relationship for the fish community, using a spatially constrained (locally calculated saturation curves within a radius of 10 to 300 km) fractal-like approximation method.
RV: species-area intercept	Research survey estimates the mean species-area intercept on the Scotian Shelf. The average scaling exponent derived from a species richness vs surface area relationship for the fish community, using a spatially constrained (locally calculated saturation curves within a radius of 10 to 300 km) fractal-like approximation method.
RV: taxonomic richness (100km)	Research survey estimates the mean number of taxa observed at 100 km^2 scale
Seal abundance adult	Abundance of seal adults
Seismic 2D; km	The length of seismic exploration tracks; km
Seismic 3D; km^2	The amount of seismic exploration conducted (3D); km^2
Shelf front: lat@-62 lon	Shelf front location at -62 longitude (latitude)
Shrimp: abundance index	Shrimp abundance index from shrimp surveys
Shrimp: capelin abundance index	Capelin abundance index for areas overlapping the shrimp fishery
Snow crab: habitat area	Snow crab survey estimates of snow crab potential habitat area (km^2) determined from temperature and depth masks
Snow crab: immature female abundance	Snow crab survey estimates of immature female abundance (no.)

Snow crab: landings	Snow crab total landings
Snow crab: male recruitment	Snow crab survey estimates of male recruitment
Snow crab: mature female abundance	Snow crab survey estimates of mature female abundance (no.)
Snow crab: mature female mean size	Snow crab survey estimates of female mean size
Snow crab: mature male biomass	Snow crab survey estimates of male mean biomass (kt)
Snow crab: mature male mean size	Snow crab survey estimates of mature male mean size
Snow crab: temperature mean	Snow crab survey estimates of mean temperature in the snow crab potential habitat
Snow crab: temperature SD	Snow crab survey estimates of the standard deviation of the mean temperature in the snow crab potential habitat
Temperature: Sable Is.	Temperature at Sable Island
Temperature: SST Halifax	Temperature: sea surface temperature at Halifax station